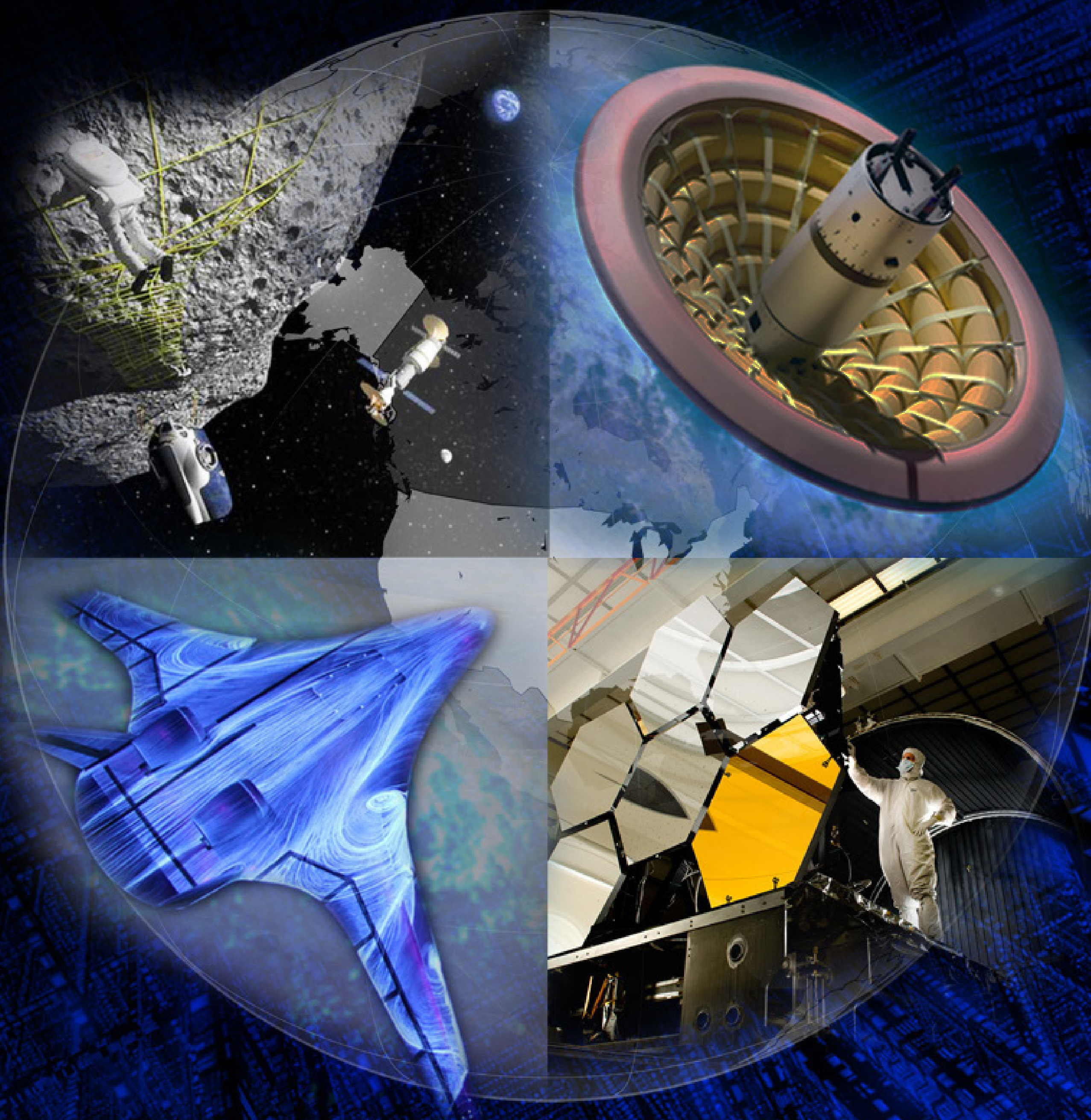
National Aeronautics and Space Administration

NASA Technology Roadmaps

TA 1: Launch Propulsion Systems



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Foreword

NASA is leading the way with a balanced program of space exploration, aeronautics, and science research. Success in executing NASA's ambitious aeronautics activities and space missions requires solutions to difficult technical challenges that build on proven capabilities and require the development of new capabilities. These new capabilities arise from the development of novel cutting-edge technologies.

The promising new technology candidates that will help NASA achieve our extraordinary missions are identified in our Technology Roadmaps. The roadmaps are a set of documents that consider a wide range of needed technology candidates and development pathways for the next 20 years. The roadmaps are a foundational element of the Strategic Technology Investment Plan (STIP), an actionable plan that lays out the strategy for developing those technologies essential to the pursuit of NASA's mission and achievement of National goals. The STIP provides prioritization of the technology candidates within the roadmaps and guiding principles for technology investment. The recommendations provided by the National Research Council heavily influence NASA's technology prioritization.

NASA's technology investments are tracked and analyzed in TechPort, a web-based software system that serves as NASA's integrated technology data source and decision support tool. Together, the roadmaps, the STIP, and TechPort provide NASA the ability to manage the technology portfolio in a new way, aligning mission directorate technology investments to minimize duplication, and lower cost while providing critical capabilities that support missions, commercial industry, and longer-term National needs.

The 2015 NASA Technology Roadmaps are comprised of 16 sections: The Introduction, Crosscutting Technologies, and Index; and 15 distinct Technology Area (TA) roadmaps. Crosscutting technology areas, such as, but not limited to, avionics, autonomy, information technology, radiation, and space weather span across multiple sections. The introduction provides a description of the crosscutting technologies, and a list of the technology candidates in each section.

Table of Contents

Executive Summary

This is Technology Area 1: Launch Propulsion Systems, one of the 16 sections of the 2015 NASA Technology Roadmaps. The Roadmaps are a set of documents that consider a wide range of needed technologies and development pathways for the next 20 years (2015-2035). The roadmaps focus on “applied research” and “development” activities.

TA 1 Launch Propulsion Systems addresses technologies that enhance existing solid or liquid propulsion technologies or their related ancillary systems. The updated 2015 NASA Technology Roadmaps includes both enabling (pull) and enhancing (push) technologies that are essential to the pursuit of NASA’s aeronautics, science, and human exploration missions, and achievement of national goals.

TA 1 is organized around six primary technology areas: 1) solid rocket propulsion systems, 2) liquid rocket propulsion systems, 3) air-breathing launch propulsion systems, 4) ancillary propulsion systems (which include subsystems for existing systems, as well as smaller rocket systems like reaction control systems (RCS) and abort systems), 5) unconventional propulsion systems, and 6) balloon systems for scientific payloads.

Solid and liquid rocket propulsion systems have been used since the dawn of spaceflight, and are comprised of fuel and oxidizers in solid or liquid form. These technologies are reaching the limits of theoretical efficiency and performance using conventional propellants. Air-breathing launch propulsion systems extract their oxidizer from the atmosphere and could be part of an integrated system that includes more conventional rockets to reach the vacuum of space. Hypersonic air-breathing systems, as demonstrated by X-43 and X-51, are still in the experimental stage. Improvements in ancillary propulsion systems would include the supporting subsystems for conventional propulsion systems, including controls and smaller rockets not directly responsible for lift to orbit. Unconventional launch technologies include systems that do not rely solely on onboard energy for launch or that use unique technologies or propellants to create rocket thrust. Included in this area are technologies that are at a very low technology readiness level (TRL) or that do not map into the other propulsion taxonomies. Balloon lift systems are used for high-altitude science and observation flights and may be considered a mature technology. For balloons lift systems, advances are needed to improve payload lift capability, altitude capability, trajectory control capability, and mission duration.

Goals

The overall goals of TA 1 technology candidates are to make access to space—specifically low-Earth orbit (LEO)—more reliable, routine, and cost effective. The primary goal of launch propulsion system technologies is to enable or enhance NASA mission launch performance. New technology candidates will be examined with the goal of reducing launch costs by a minimum of 50 percent over the next 20 years. Launch cost reductions will be beneficial to NASA, other government agencies, and the commercial launch industry. A secondary goal is to provide increased sea level thrust output on large human-rated vehicles. The third goal of this technology area is specifically related to balloon systems, and is to increase mission duration to 100 days.

Table 1. Summary of Level 2 TAs

1.0 Launch Propulsion Systems	Goals:	Make access to space more reliable, routine, and cost effective.
1.1 Solid Rocket Propulsion Systems	Sub-Goals:	Increase performance and safety while reducing cost.
1.2 Liquid Rocket Propulsion Systems	Sub-Goals:	Improve the production and manufacturability of large booster engines to reduce cost without sacrificing performance or reliability.
1.3 Air Breathing Propulsion Systems	Sub-Goals:	Aeronautic application goals are addressed in the Roadmap for TA 15 (Aeronautics). There are no earth-to-orbit goals at this time.
1.4 Ancillary Propulsion Systems	Sub-Goals:	Enhance vehicle production and improve overall vehicle reliability and safety while reducing operational costs.
1.5 Unconventional and Other Propulsion Systems	Sub-Goals:	Provide affordable launch-on-demand capability in new nano and micro satellite markets.
1.6 Balloon Launch Systems	Sub-Goals:	Develop new vehicles and support components to enhance support for balloon launch systems.

Benefits

While solid and liquid propulsion systems continue to meet critical national needs and are reaching the theoretical limits of efficiency, they have known operational and cost challenges. Improvements in launch propulsion systems and their ancillary systems will be instrumental in maintaining the Nation's historic leadership role in space launch capability.

The overall goals of TA 1 developments within NASA are to make access to space—specifically LEO—more reliable, routine, and cost effective. At present, solid and liquid rocket-based propulsion systems are the primary means for the U.S. to launch payloads to LEO. Given the Nation's near-term dependence on space-based assets in LEO and other orbits, it is vital that the Nation maintain its industrial capability to design, build, test, and fly state of the art solid and liquid rockets. NASA development of technologies that enable and enhance these systems will ensure that LEO remains accessible.

Advanced capabilities in launch propulsion systems will support NASA's missions and are extensible to other government agencies and the commercial sector. All space-fairing organizations would greatly benefit from the reduced costs, improved reliability, and greater utility of new launch systems enabled through development of the technology candidates proposed in TA 1.

Over the last 15 years, the U.S. aerospace industry has been detrimentally impacted by the loss of several key U.S. technology capabilities that enable access to space. In addition, the Nation has come to rely on foreign suppliers that put restrictions on the use of their supplied technologies, such as oxygen-rich staged combustion (ORSC) engines. These restrictions have a significant impact and can only be addressed by creating a domestic supply base for these critical components and technologies.

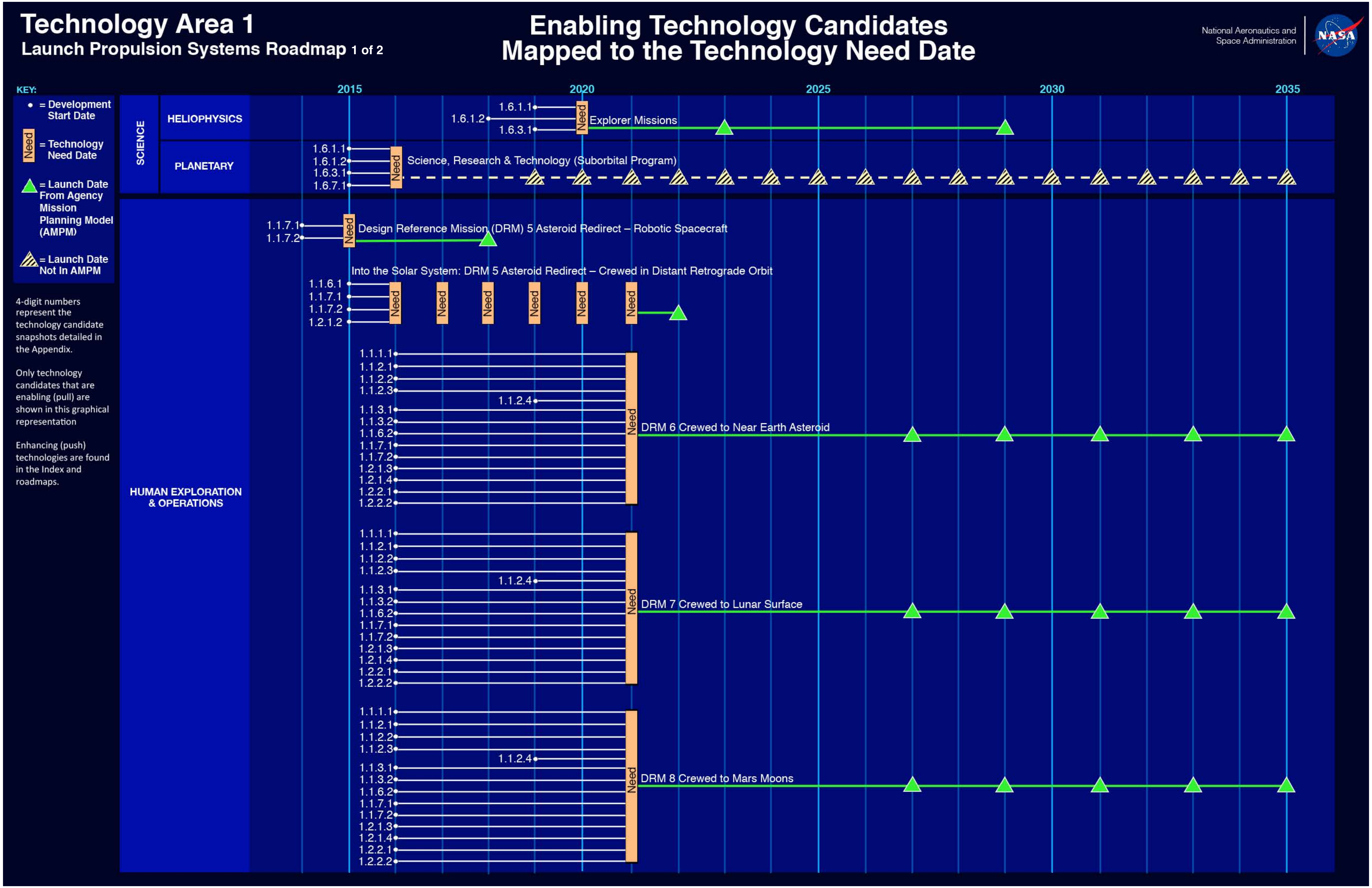

Figure 1. Technology Area Strategic Roadmap

Technology Area 1

Launch Propulsion Systems Roadmap (cont.) 2 of 2

Enabling Technology Candidates Mapped to the Technology Need Date

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KEY:

- • = Development Start Date
- Need = Technology Need Date
- = Launch Date From Agency Mission Planning Model (AMPM)
- = Launch Date Not In AMPM

4-digit numbers represent the technology candidate snapshots detailed in the Appendix.

Only technology candidates that are enabling (pull) are shown in this graphical representation

Enhancing (push) technologies are found in the Index and roadmaps.

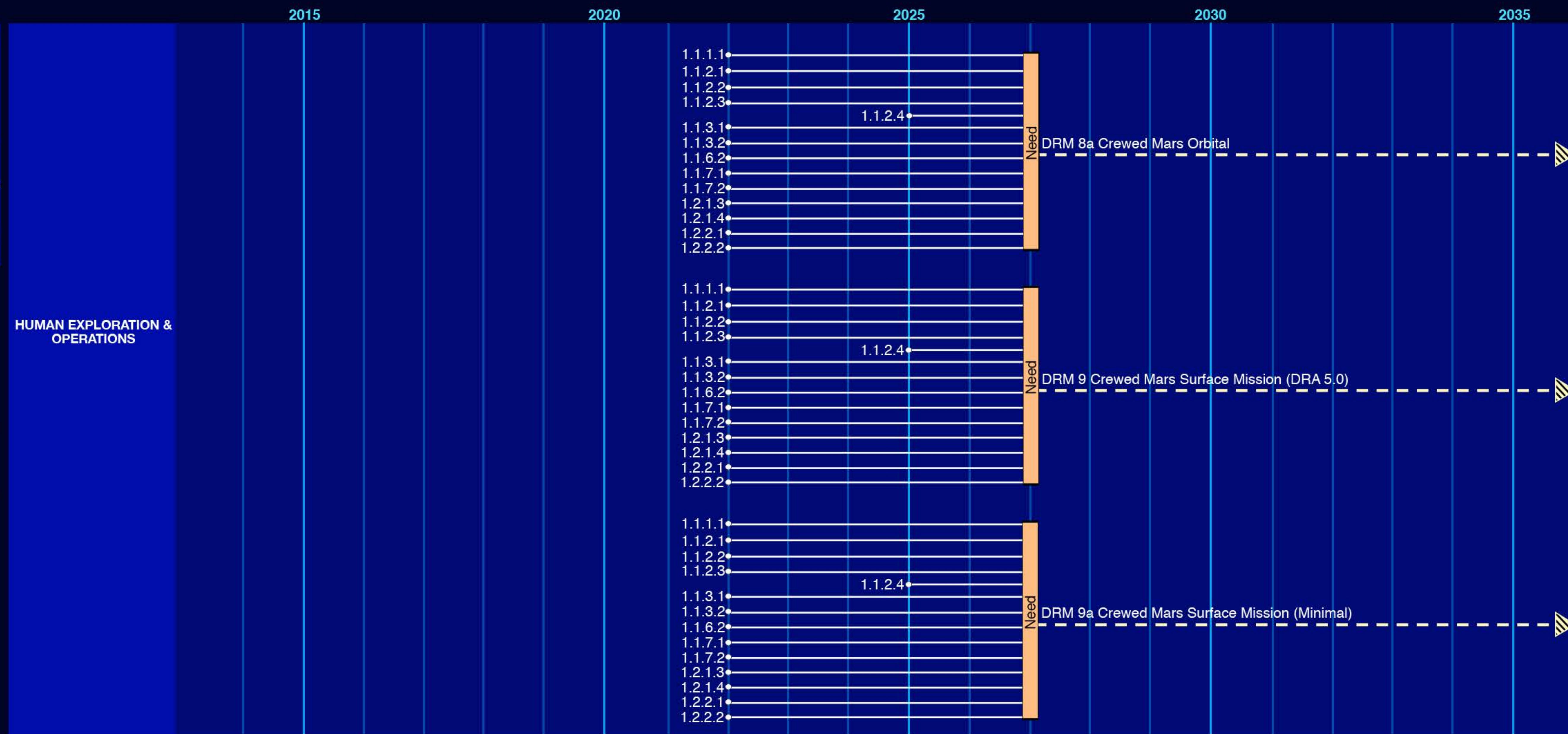


Figure 1. Technology Area Strategic Roadmap (Continued)

Introduction

Space lift to Earth orbit involves escaping the Earth's gravitional field to deliver a spacecraft to conduct its mission in Earth orbit or beyond. Low-Earth orbit (LEO) is considered to start at approximately 200 miles high, and the launch propulsion system's challenge is to impart at least the orbital insertion velocity to the spacecraft in the most afforable and effective manner. To this end, the launch propulsion system can include a number of approaches, such as multiple types of propulsion systems (e.g., solid rockets, liquid rocket, or air breathing rockets) or combinations thereof. Further, whatever the type of propulsion system, ancillary propulsion systems are necessary to provide certain functions such as aborts or thrust vectoring. Additionally, while conventional space lift relies upon solid and liquid propellant rockets, there are balloon-based systems for high-altitude research applications, and the promise of future unconventional systems not yet demonstrated today.

Figure 2 shows the technologies associated with the Launch Propulsion Systems technology area. Each technology is described in this section. Light gray text indicates technology areas from the 2010 technology roadmap that are not fully developed in this roadmap because they are sufficiently advanced or they do not provide needed capabilities for a planned or potential future NASA mission class, design reference mission, or aeronautic thrust area identified by the Human Exploration Architecture Team, the Science Decadals, and the Aeronautics Research Plan respectively.

1.1 Solid Rocket Propulsion Systems

Chemical solid and liquid rocket propulsion systems have been used since the dawn of spaceflight, and as their names suggest, consist of fuel and oxidizers in solid or liquid form. These technologies are reaching the limits of theoretical efficiency and performance using conventional propellants.

Solid rocket motors (SRMs) have some advantages over liquid systems, such as high energy density and long-term stability and storability. However, certain disadvantages limit their applicability, and can be reduced or eliminated by advancing the technology base of SRMs to make them more attractive alternatives to liquid rocket systems. Key disadvantages for SRMs are lower performance or specific impulse (I_{sp}), lack of throttling on demand, an inability to shut down on command, environmental concerns, and ground operations costs associated with safety issues in handling large solid segments. This roadmap proposes technology developments that address some of these disadvantages and enhance the inherent advantages mentioned above.

Key areas for improvement include developing a green (environmentally compatible, non-toxic, and non-carcinogenic) propellant alternative to current oxidizers, advancing the ability to assess damage tolerance limits and detect damage on composite cases, developing domestic sources for critical materials used in manufacturing of SRMs, formulating advanced hybrid fuels to get energy density equal to SRMs, and advancing the fundamental physics of SRM design including analysis and design tools.

From a systems viewpoint, the SRM is composed of the igniter, case, liner, insulation, nozzle, and propellants. The Space Shuttle (Shuttle) solid rocket booster (SRB) is the largest SRM referenced in advancing the state of the art.

- **1.1.1 Propellants:** An alternate SRM propellant for large booster motors is needed to provide higher performance power density and to provide commonality with other SRM systems. For example, the switch from Polybutadiene Acrylic Acid Acrylonitrile Prepolymer (PBAN) that was used by the Shuttle SRB to Hydroxyl Terminated Poly Butadiene (HTPB) for the advanced Space Launch System (SLS) five-segment SRB will provide the higher I_{sp}, performance and high-power density required to evolve the SLS system to the 130 metric ton (mt) vehicle.

TA 1 Launch Propulsion Systems

1.1 Solid Rocket Propulsion Systems

- 1.1.1 Propellants
- 1.1.2 Case Materials
- 1.1.3 Nozzle Systems
- 1.1.4 Hybrid Rocket Propulsion Systems
- 1.1.5 Fundamental Solid Propulsion Technologies
- 1.1.6 Integrated Solid Motor Systems
- 1.1.7 Liner and Insulation

1.2 Liquid Rocket Propulsion Systems

- 1.2.1 LH2/LOX Based
- 1.2.2 RP/LOX Based
- 1.2.3 CH4/LOX Based
- 1.2.4 Detonation Wave Engines – Closed Cycle
- 1.2.5 Propellants
- 1.2.6 Fundamental Liquid Propulsion Technologies

1.3 Air Breathing Propulsion Systems

- 1.3.1 Turbine-Based Combined-Cycle
- 1.3.2 Rocket-Based Combined Cycle
- 1.3.3 Detonation Wave Engines – Open Cycle
- 1.3.4 Turbine-Based Jet Engines
- 1.3.5 Ramjet and Scramjet Engines
- 1.3.6 Deeply-Cooled Air Cycles
- 1.3.7 Air Collection and Enrichment Systems
- 1.3.8 Fundamental Air Breathing Propulsion Technologies

1.4 Ancillary Propulsion Systems

- 1.4.1 Auxiliary Control Systems
- 1.4.2 Main Propulsion Systems (Excluding Engines)
- 1.4.3 Launch Abort Systems
- 1.4.4 Thrust Vector Control Systems
- 1.4.5 Health Management and Sensors
- 1.4.6 Pyro and Separation Systems
- 1.4.7 Fundamental Ancillary Propulsion Technologies

1.5 Unconventional and Other Propulsion Systems

- 1.5.1 Ground Launch Assist
- 1.5.2 Air Launch and Drop Systems
- 1.5.3 Space Tether Assist
- 1.5.4 Beamed Energy and Energy Addition
- 1.5.5 Nuclear
- 1.5.6 High Energy Density Materials and Propellants

1.6 Balloon Launch Systems

- 1.6.1 Super-Pressure Balloon
- 1.6.2 Materials
- 1.6.3 Pointing Systems
- 1.6.4 Telemetry Systems
- 1.6.5 Balloon Trajectory Control
- 1.6.6 Power Systems
- 1.6.7 Mechanical Systems – Launch Systems
- 1.6.8 Mechanical Systems – Parachute
- 1.6.9 Mechanical Systems – Floatation

Figure 2. Technology Area Breakdown Structure Technology Areas for Launch Propulsion Systems

NASA's technology area breakdown structure (TABS) is in wide use in technology organizations around the globe. Because of this, any sections that were previously in the structure have not been removed, although some new areas have been added. Within these roadmaps, there were some sections of the TABS with no identified technology candidates. This is either because no technologies were identified which coupled with NASA's mission needs (either push or pull) within the next 20 years, or because the technologies which were previously in this section are now being addressed elsewhere in the roadmaps. These sections are noted in gray above and are explained in more detail within the write-up for this roadmap.

- **1.1.2 Case Materials:** The SRM case is designed as a pressure vessel to take internal pressure loads, all flight attachment loads, and ground handling loads. The Shuttle SRB used metal cases. The SLS Advanced Booster needs a composite case manufacturing capability for a large booster motor, along with damage tolerance detection methods, handling of large composite segments, and methods for joining a composite membrane to a metal joint ring. These developments support evolution of the SLS to the 130 mt vehicle. SRM systems need alternate case manufacturing methods, such as additive manufacturing, to produce cases with reduced weight, cost, and schedule.
- **1.1.3 Nozzle Systems:** The function of a nozzle is to control expansion of the chamber gas by efficiently converting energy forms in the chamber to kinetic energy (impart thrust to the vehicle) and, in some applications, control the thrust vector. Nozzles for large SRMs can be quite complex; contain many parts; consume considerable design, analysis, and fabrication time for an SRM; and may be required to gimbal to control the thrust vector such as was required by the Shuttle SRB's nozzle. Lightweight, low-erosion materials are needed to reduce weight and improve performance. Large SRMs need a flex bearing that replaces the current flex boot design.
- **1.1.4 Hybrid Rocket Propulsion Systems:** Hybrid motors differ from solid and liquid rocket systems in that they typically combine a solid fuel with a liquid oxidizer. The hybrid fuel is contained within the combustion chamber and the oxidizer is fed from an oxidizer tank. The oxidizer tank can be part of the same structure or a separate component. There are opportunities for development in fuel oxidizer combinations, grain design, system design and combustion processes. Low-cost hybrid rocket motors need to be developed for use as propulsion for launch vehicles capable of delivering nano and micro satellites (nano: 1 kilogram (kg)-10 kg; micro: 10 kg -100 kg) into LEO and other possible applications. This would include a hybrid rocket motor stage for a small nano-launcher class vehicle. Hybrid rocket propulsion systems have advantages and disadvantages just like any other rocket propulsion system. The advantages of hybrids are reduced cost, ability to throttle, improved safety, ability to restart, and propellant selection. Hybrids also have some disadvantages, such as low combustion efficiency in large ports, low regression rate, and mass fraction. The current hybrid rocket motor propulsion focus is on pursuing technologies that will drastically reduce propulsion cost and delivery time, including the development of additive manufacturing methods to produce such things as domes, motor cases, and print propellants; development of high-regression fuels and multiport, multi-row grain technology; and combustion stability enhancement techniques.
- **1.1.5 Fundamental Solid Propulsion Technologies:** Advanced, robust, reduced-cost motors will incorporate advanced technology in the areas of propellants, case, liner, insulation materials, and nozzles. Validated, high-fidelity, physics-based analytical tools must be available to support the timely design, development, test, and evaluation (DDT&E) of these new components and systems. Experimentally-derived propulsion environments are needed for validation of these tools and to enhance technical understanding. Also, data acquisition and measurement technologies are needed for detailed characterization of these environments.
- **1.1.6 Integrated Solid Motor Systems:** A new large SRB booster is needed that incorporates advanced propellants, case materials, liner and insulation, and nozzle design technologies to meet mission requirements to evolve the SLS to a 130 mt vehicle for solar system exploration.
- **1.1.7 Liner and Insulation:** Internal insulation in an SRM is a layer of heat barrier material placed between the internal surface of the case and the propellant. The primary function of internal insulation is to prevent the case from reaching temperatures that endanger its structural integrity. It functions secondarily to prevent impingement of combustion products on the case and to seal the case, joints, and fittings from hot combustion products. The liner material provides a bond between the insulation and the propellant in SRMs, and therefore must be compatible with the selected insulation and propellant. The liner must have acceptable aging characteristics to maintain the insulation, liner, and propellant bond throughout the service life of the SRM. An asbestos-free liner and insulation replacement system must be developed to maintain structural integrity of the SLS' SRB.

1.2 Liquid Rocket Propulsion Systems

Liquid rocket propulsion systems use propellants (fuels and oxidizers) that are kept in a liquid state prior to and during flight. The advantages of liquid rocket engines include generally higher I_{sp} and better thrust control (including throttling and restart capability) than SRMs. Some disadvantages of liquid rocket propulsion systems are that they are more operationally complex than solids and require some form of active flow control that introduces additional possibilities for failures. For Earth-to-orbit applications, the primary delivery system for the propellants to the thrust chamber is via turbo machinery that raises the propellant pressures sufficiently to support the high-pressure combustion process.

- **1.2.1 LH_2/LOX Based:** A liquid rocket engine that utilizes liquid hydrogen (LH_2) and liquid oxygen (LOX) as the propellants. These propellants are classified as cryogenic propellants because of the very low temperatures that are required to keep the propellants in liquid state. Typical storage temperatures and densities for LH_2 are approximately 38 degrees Rankine (° R) at approximately four pounds mass (lbm) per cubic foot. LOX temperatures and densities are approximately 170° R at approximately 72 lbm per cubic foot. The very low temperature and density of LH_2 creates unique challenges for handling and delivering the propellant to the thrust chamber for combustion.
- **1.2.2 RP/LOX Based:** A liquid rocket engine that utilizes kerosene-based rocket propellant (RP) and LOX as the propellants. The kerosene-based RP is room temperature storable with a density of approximately 52 lbm per cubic foot. The cryogenic LOX temperatures and densities are approximately 170° R at ~72 lbm per cubic foot.
- **1.2.3 CH_4/LOX Based:** A liquid rocket engine that utilizes liquid methane (CH_4) and LOX as the propellants. These propellants are classified as cryogenic propellants because of the very low temperatures that are required to keep them in a liquid state. Typical storage temperature and density for liquid CH_4 are approximately 200° R and approximately 27 lbm per cubic foot. Typical LOX storage temperature and density are approximately 170° R at approximately 72 lbm per cubic foot.
- **1.2.4 Detonation Wave Engines (Closed Cycle):** Detonation wave engines operate by injecting propellants into long cylinders that are open on one end and closed on the other. When gas fills a cylinder, an igniter—such as a spark plug—is activated. Fuel begins to burn and rapidly transitions to a detonation, or powered shock. The shock wave travels through the cylinder at 10 times the speed of sound, so combustion is completed before the gas has time to expand. The explosive pressure of the detonation pushes the exhaust out the open end of the cylinder, providing thrust to the vehicle. This process allows the propellants to be injected at much lower pressures than conventional continuous-burning rocket engines, simplifying the requirements of the propellant delivery system.
- **1.2.5 Propellants:** Advanced exotic propellants that demonstrate advantages over currently available propellant options.
- **1.2.6 Fundamental Liquid Propulsion Technologies:** This consists of crosscutting basic design and manufacturing technologies that support rapid, highly integrated, multidisciplinary liquid rocket engine design, development, and production.

1.3 Air-Breathing Propulsion Systems

Air-breathing launch propulsion systems use atmospheric oxygen and could be part of an integrated system that includes more conventional rockets to reach the vacuum of space. Air-breathing systems may be highly-integrated, multi-mode, combined-cycle systems, or a combination of more discrete systems. They may be used in a first stage to provide the flexibility of runway-launch for small payloads, or in an integrated system to provide high I_{sp} performance over a wider speed range. Weight, complexity, and more severe vehicle system environments are factors that mitigate increased air-breathing I_{sp} performance and must be carefully considered in any implementation. Dual-mode scramjet systems, operable over the Mach 5-10 speed range have been demonstrated in flight (X-43 and X-51) but are still considered experimental.

While acknowledging that air-breathing propulsion in various forms may offer advantages in launch flexibility, reusability, and cost for some types of Earth-to-orbit missions, NASA is not currently advancing any air-breathing technologies for NASA missions. However, NASA supports other government-funded activities in this area.

- **1.3.1 Turbine-Based Combined-Cycle:** A combination propulsion system that consists of a turbine engine and ram or dual-mode scramjet. Concepts generally employ separate ducts for the turbine engine and ramjet flows, although a common variable-geometry inlet or nozzle is often proposed.
- **1.3.2 Rocket-Based Combined-Cycle:** A combined-cycle propulsion system that generally consists of an ejector-ramjet or rocket mode for liftoff, followed by ramjet, scramjet, and rocket modes for acceleration to orbital velocity. Synergy between the various cycles is taken advantage of by using a common variable-geometry flow-path for all modes.
- **1.3.3 Detonation Wave Engines (Open Cycle):** Detonation wave engines operate by injecting fuel and air into a tube that is open on one end and closed on the other. When gas fills the cylinder, an igniter is activated and initiates a detonation and constant-volume combustion process, pressurizing the head end and providing a thrust impulse. As the combustion products exit the tube, a rarefaction wave travels back upstream to the head end and the cycle is repeated.
- **1.3.4 Turbine Based Jet Engines (Flyback Boosters):** Adaptation of conventional jet engines as flyback booster engines designed to withstand the launch environment imposed by a conventional vertical rocket launch.
- **1.3.5 Ramjet and Scramjet Engines (Accelerators):** Adaptation of traditional ramjet and scramjet air breathing propulsion systems to provide acceleration of an Earth-to-orbit launch system within the atmosphere. Important aspects of these systems include maximizing thrust-to-weight ratio and a high degree of integration with the launch vehicle.
- **1.3.6 Deeply-Cooled Air Cycles:** Advanced deeply-cooled air engine cycle technology development to apply to launch systems as atmospheric accelerators. Includes subsystem and system technologies.
- **1.3.7 Air Collection and Enrichment System:** Concepts for collecting and liquefying air to be used as the oxidizer for a liquid rocket propulsion system that would reduce the gross lift-off weight of the vehicle system.
- **1.3.8 Fundamental Air-Breathing Propulsion Technologies:** Crosscutting basic design and manufacturing technologies that support air-breathing propulsion system design, development, and production. Examples include high-temperature lightweight materials, supersonic combustion, and numerical design, analysis, and optimization tools.

1.4 Ancillary Propulsion Systems

Ancillary propulsion systems provide additional launch vehicle propulsion functions, other than primary ascent. These systems include both mechanical and propulsive control systems, such as Thrust Vector Control (TVC), Main Propulsion Systems, Reaction Control Systems (RCS), and Roll Control Systems (RoCS). Also included are propulsive systems for separation (separation motors) and propellant management (ullage settling motors), as well as systems for crew safety (abort propulsion systems). Propulsive elements of these ancillary systems are commonly provided by both SRMs and pressure-fed liquid propulsion thrusters (both mono-propellant and bi-propellant). Mechanical control functions historically have been provided through hydraulic systems. However, more recently these functions are also beginning to be provided through electromechanical and electrohydraulic systems. Improvements in ancillary propulsion systems would include the supporting subsystems for conventional propulsion systems, such as controls and smaller rockets not directly responsible for lift to orbit.

- **1.4.1 Auxiliary Control Systems:** Small propulsion systems that provide position control, attitude control, roll maneuvers during ascent flight, and post-staging periods to achieve desired orientations.
- **1.4.2 Main Propulsion Systems (Excluding Engines):** Vehicle fluid systems that support the liquid main engine operation by providing a means of integration between the engine, vehicle systems, propellant tanks, and ground systems.
- **1.4.3 Launch Abort Systems:** Propulsion systems—both solid and liquid—that are used to rapidly separate and distance the crew from a dangerous vehicle system failure.
- **1.4.4 Thrust Vector Control Systems:** Mechanical systems that alter the direction of the thrust vector and, if desired, its resulting point of application on the vehicle.
- **1.4.5 Health Management and Sensors:** Electronics and algorithms that provide real-time diagnostics of propulsion systems' health status to support navigation and mission decision-making.
- **1.4.6 Pyro and Separation Systems:** Mechanical and pyrotechnic components that sever the physical connections between launch vehicle elements.
- **1.4.7 Fundamental Ancillary Propulsion Systems:** Crosscutting, advanced design tools and manufacturing technologies that support ancillary propulsion system design, development, and production.

1.5 Unconventional and Other Propulsion Systems

Unconventional launch technologies include systems that do not rely solely on onboard energy for launch or that use unique technologies or propellants to create rocket thrust. Included in this area are technologies that are at a very low Technology Readiness Level (TRL) or that do not map into the other propulsion taxonomies. This roadmap only includes new technology candidates for air launch and drop systems, which have options supporting the emerging capability for nano or small satellite deployment. At this time, no other technology candidates were proposed that provided capabilities needed for achievement of NASA's aeronautics, science, or exploration missions.

- **1.5.1 Ground Launch Assist:** Ground Launch Assist includes technologies to horizontally accelerate the launch vehicle to offload a small portion of the vehicle propellant needed to achieve the final vehicle escape velocity to reach LEO. By making the vehicle smaller, the cost of the vehicle should be reduced. Example systems are steam catapult or magnetic-rail launch assist.
- **1.5.2 Air Launch and Drop Systems:** Air launch and drop systems include technologies that provide initial stage delta-V by lifting the launch vehicle to a high altitude and releasing the vehicle before it ignites the onboard propulsion systems. This approach also offloads a small portion of the vehicle propellant needed to achieve the final escape velocity required to reach LEO.
- **1.5.3 Space Tether Assist:** Space tether assist is the concept of using a rotating tether anchored in space, which can be used to catch upper stages or payloads and impart orbital momentum to elevate them to orbit.
- **1.5.4 Beamed Energy and Energy Addition:** Beamed energy is a form of propulsion that uses energy beamed to the spacecraft from a remote power plant to provide energy. Most designs are thermal rockets where the energy is provided by the beam, and is used to superheat propellant that then provides propulsion. However, some obtain propulsion directly from light pressure acting on a light sail structure, and at low altitude heating air gives extra thrust.
- **1.5.5 Nuclear:** A nuclear reaction process provides the thermal energy necessary to heat the propellant and accelerate the vehicle. The reaction process can be fission or fusion.

- **1.5.6 High Energy Density Materials and Propellants:** Advanced exotic propellants that are major improvements over currently available propellant options.

1.6 Balloon Launch Systems

NASA uses balloon launch systems to provide high-altitude platforms for scientific and technological investigations. These investigations include fundamental scientific discoveries that contribute to our understanding of Earth, the solar system, and the universe. Scientific balloons also provide a platform for demonstrating promising new instrument and spacecraft technologies.

- **1.6.1 Super-Pressure Balloon:** A style of aerostatic balloon where the volume of the balloon is kept relatively constant in reaction to changes in the temperature of the contained lifting gas. Current NASA Scientific Balloon vehicles are vented designs with zero differential pressure at the base of the balloon. Super-pressure balloons (SPBs) allow longer flight durations and minimize altitude loss during nighttime conditions. SPBs enhance existing science support capabilities.
- **1.6.2 Materials:** Current balloon payloads and flight trains use conventional steel and aluminum materials for mechanical structures and assemblies. Lighter-weight materials would enhance available mass for science instruments on balloon payloads.
- **1.6.3 Pointing System:** The current balloon standard positioning system provides azimuth pointing with accuracy and knowledge of approximately 2 degrees. Two- or three-axis fine pointing capabilities with accuracy of approximately 1 arc second enables advanced exoplanet, planetary, and Earth science missions on balloon platforms.
- **1.6.4 Telemetry Systems:** Balloon science users typically collect more scientific data than can be downloaded in real-time during flight. The current telemetry capability provides approximately 150 kilobits per second (kbps) using satellite relay. Higher downlink bit rate capability enhances science data downlink throughput during flight.
- **1.6.5 Balloon Trajectory Control:** Longer-duration flights could be enhanced by modifying the free-floating balloon's trajectory. Trajectory control would allow for both avoiding overflight of populated areas as well as guiding systems to safe termination areas at the end of the flight.
- **1.6.6 Power Systems:** Science users require power systems with more capability for higher-power science instruments. Advancements are needed in power generation and in power storage for night time exposure.
- **1.6.7 Mechanical Systems–Launch Systems:** The current NASA Scientific Balloon launch systems are manually operated in close proximity to the balloon vehicle and payload systems. Launch systems that can be operated remotely enable launch of more hazardous payloads and enhance the safety of launch operations.
- **1.6.8 Mechanical Systems–Parachute:** Current NASA Scientific Balloon parachutes consist of nylon, which is susceptible to ultraviolet degradation. Addition of ultraviolet protection systems will enhance the duration of balloon missions.
- **1.6.9 Mechanical Systems–Floatation:** Longer-duration balloon flights in mid latitudes will spend long periods over the southern oceans. There is a potential of termination over the ocean, and flotation is desired so the payload systems can be recovered.

TA 1.1: Solid Rocket Propulsion Systems

Solid rocket motors (SRMs) have many advantages over liquid systems, such as high energy density and long-term stability and storability. Key disadvantages for SRMs today are lower performance (I_{sp}), lack of throttling on demand or ability to shut down on command, environmental concerns, and ground operations costs associated with safety issues in handling large solid segments. Through technology development, these disadvantages can be reduced or eliminated, enabling realization of the advantages that make SRM more attractive than liquid systems.

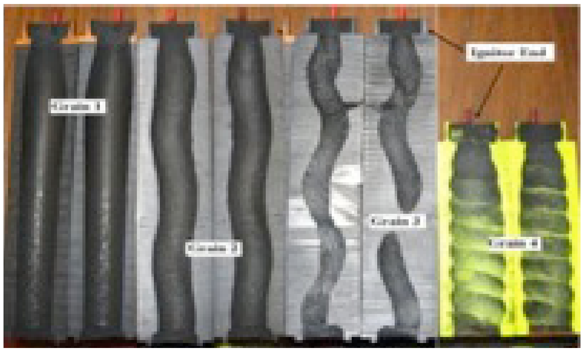
Additively Manufactured Solid Motor Domes

SRMs are characterized by the highest thrust-to-weight, highest density impulse, and highest acceleration of any chemical propulsion technology. These characteristics provide mission designers with tools and capabilities to meet performance requirements for the launch vehicle's boost phase. The Shuttle SRB represents the state of the art (SOA) for large human-rated SRMs. A SRB is an SRM configured for flight (includes nose cone, electrical systems, thrust vector control, attachment hardware, etc.).

The technical characteristics of SRM that make them desirable include their high level of readiness and operational simplicity, rapid acceleration with near-instantaneous levels of maximum thrust, very high thrust capabilities, and high impulse-density levels, which minimize the volumetric size of propulsion systems. Solid motors help minimize gravity loss by utilizing a very short boost phase, which can greatly reduce launch vehicle performance requirements. Without SRMs and their high thrust potentials and high impulse density, it would be difficult to develop an optimal solution for a heavy-lift vehicle with a capability of 130 mt or greater to LEO.

Two types of SRMs exist: monolithic and multi-segment designs. Large monolithic (less than 350,000 lbm of propellant) solid motors may provide interesting trades compared to large segmented solids for use in heavy-lift launch vehicles.

The unique characteristics of a SRM make it well suited for space launch systems that need high levels of readiness, rapid acceleration, or design simplicity (e.g., no moving parts) for reliability and safety. Another useful characteristic of SRMs is their ability to have efficient, compact packaging, which leads to low inert masses and high mass fractions. Mass fraction is the percentage of the rocket that is transferred into energy (propellant) compared to total mass including inert mass (structures, insulation, tanks, etc.). Higher mass fractions lend themselves to less energy losses within Earth's deep gravity well, which translates into more volumetric- and gross-mass efficient vehicles. A SRM primarily consists of six major components: igniter, case, insulation, liner, propellant, and nozzle.



Printed Solid Motor Fuel Grain

Sub-Goals

Human exploration missions into the solar system, to explore other worlds and planets, require technology advancements for human-rated large solid rocket motors that can support a 130 mt payload. The propulsion capability includes the higher-performing HTPB propellant, over the current PBAN propellant. An important objective is to develop the ability to manufacture larger (13.4 foot (ft) diameter) composite motor cases, which must weigh less than the 12 ft diameter metal cases currently used. Damage tolerance and damage detection methods, and material tolerance limits for composite cases need to be developed to ensure the integrity of their human-rating. The larger-diameter composite case will need manufacturing technology that improves the interface between the composite case membrane joint and its metal joint rings. To reduce manufacturing cost and weight, developing a replacement for current asbestos-based liners and insulation (e.g., insulating or ablative sprayable liner and insulation) is also required. Other areas targeted for weight savings and reliability improvements are a low-weight or low-erosion nozzle and expanding flex bearing with eroding shims. These technologies, incorporated into a new booster system, would increase the sea level thrust of the SRB to the 4,500 thousand pounds of thrust (klbf) required to meet the design requirements of the 130 mt vehicle.

SLS-sized large hybrid boosters are not being pursued at this time. However, there is a need for small hybrids that support low-cost propulsion for nano-launcher class vehicles. Currently, small satellites depend on ride sharing on large vehicles for launches, which are subject to time and orbit constraints. The current cost to launch a 100 lbm payload to LEO on a dedicated launcher is $10 million. The objective for nano-launcher class vehicles of the same payload class is to lower that cost to $1.5 million. This will be achieved by manufacturing low-cost SRM hardware using additive manufacturing methods. The ability to print motor cases, case domes, propellants, injectors, valves, and small tanks provides an opportunity to reduce the time and cost of producing hardware and ultimately the cost of launching small satellites. The nano-launcher class work supports NASA's Science, Research, and Technology (suborbital program) mission, the Earth Venture Suborbital mission, and the Explorer missions. It would also support the need to launch small satellites at any time for situational awareness for a variety of government applications.

Table 2. Summary of Level 1.1 Sub-Goals, Objectives, Challenges, and Benefits

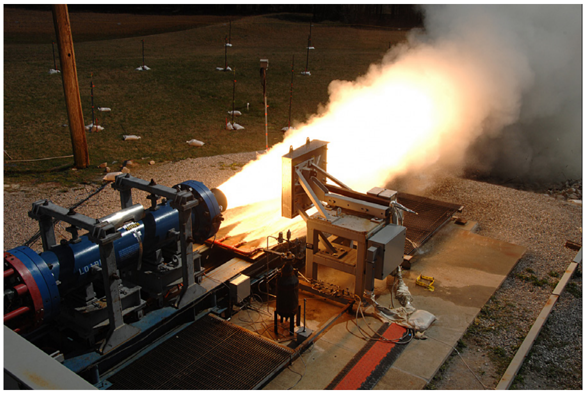
Level 1		
1.0 Launch Propulsion Systems	Goals:	Make access to space more reliable, routine, and cost effective.
Level 2		
1.1 Solid Rocket Propulsion Systems	Sub-Goals:	Increase performance and safety while reducing cost.
Level 3		
1.1.1 Propellants	Objectives:	Increase performance, specific impulse, and density.
	Challenges:	Formulations that meet performance and mechanical properties as well as scale-up.
	Benefits:	Provides high performance, HTPB-based solid propellant for a 130 mt vehicle.
1.1.2 Case Materials	Objectives:	Replace 12 ft diameter metal SRM cases with up to 13.4 ft diameter composite cases with same reliability but with reduced cost and increased mass fraction.
	Challenges:	Composite case scaling for up to 13.4 ft and joining to metallic rings. Scale-up of 3D printing technology and incorporating dual material printing to create hybrid metallic or composite structures.
	Benefits:	Creates large-diameter boosters by damage tolerance and detection methods for the SLS Advanced Development Office (ADO) Risk Reduction program. Scales-up 3D printing technology and incorporating dual material printing to create hybrid metallic or composite structures.
1.1.3 Nozzle Systems	Objectives:	Develop an ablative material that is low density and low erosion to reduce weight for a large SRM. Develop a flex bearing for a large SRM that uses eroding shims instead of a flex boot for thermal protection.
	Challenges:	Formulating new lightweight materials that have low erosion rates and do not have ply lift or pocketing.
	Benefits:	Reduces weight in larger-diameter SRM components.
1.1.4 Hybrid Rocket	Objectives:	Provide low-cost hybrid rocket for launch vehicles capable of delivering nano and micro satellites into LEO.
	Challenges:	Launch on demand.
	Benefits:	Reduces the cost of launch vehicle such as launcher, launch site, launcher process, and others.
1.1.5 Fundamental Solid Propulsion Technologies	Objectives:	Provide physics-based models for design and analysis of large SRMs.
	Challenges:	Coupling different physics-based models.
	Benefits:	Reduces design cost and time, reduces the number of required tests, and provides additional insight into tests that are conducted.
1.1.6 Integrated Solid Motor Systems	Objectives:	Increase performance and reduce mass to enable larger launched payload masses.
	Challenges:	Liners and insulation.
	Benefits:	Allows the development of the large high-performance SRB required for the 130 mt payloads while reducing overall system cost.
1.1.7 Liner and Insulation	Objectives:	Develop asbestos-free SRM case liner and insulation materials that still maintain the SRM internal case temperature below the thermal limits.
	Challenges:	Polybenzimidazole (PBI) processing.
	Benefits:	Eliminates health issues by developing an asbestos-free liner and insulation system within thermal limits. Reduces weight, eliminates process issues being addressed today, and maintains the SRB internal case within temperature limits.

TA 1.1.1 Propellants

Large Segmented RSRM Test

The SOA for large segmented SRMs that are human-rated is the Shuttle SRB, which is a four-segment design. The current SLS five-segment design uses the same propellant binder, PBAN. Most other large solid rocket motors developed after the reusable solid rocket motor (RSRM) all use HTPB. Solid propellants are composed of an oxidizer—usually ammonium perchlorate—a fuel like aluminum, a polymeric binder, and a rubber. The type of polymer binder used classifies composite propellants. In the case of the Shuttle SRB, PBAN was used as the binder. Improved SRM performance is required to support the evolution of the 70 mt SLS vehicle to the 130 mt vehicle design to support solar system exploration missions. An alternative to PBAN is HTPB propellant formulation, which will provide increased performance, I_{sp}, and density. Under SLS advanced booster development, HTPB propellant formulation work is being conducted to determine the optimum propellant formulation to achieve the required performance goals and mechanical properties. HTPB is currently being used in smaller solid motors and missile applications. Very large segmented (12 ft diameter) SRBs are needed to meet the SLS mission needs.

Technical Capability Objectives and Challenges



24-inch Motor Test

A formulation for HTPB propellant must be developed for a human-rated large solid motor that can support Design Reference Missions (DRMs) 6, 7, 8, 8a, 9, 9a (Into the Solar System, Exploring Other Worlds, and Planetary Exploration). An HTPB propellant formulation would increase performance, I_{sp}, and density. The objective for I_{sp} is a range of 265-300 seconds and the density goal is > 0.68 lbm/inch^3. HTPB propellant formulations are currently being worked under the SLS Advanced Development Office's (ADO) technology risk reduction program. The current HTPB effort is exploring formulations that meet performance and mechanical properties as well as scale-up. HTPB is currently used on smaller missiles and tactical systems.

Benefits of Technology

Higher performance, HTPB-based solid propellant is required for human-rated vehicles, to go from 70 mt to a 130 mt vehicle. Technology work on scaling the use of HTPB propellant to large (up to 13.4 ft) diameter boosters is currently ongoing.

Table 3. TA 1.1.1 Technology Candidates – not in priority order

TA	Technology Name	Description
1.1.1.1	Hydroxyl Terminated Polybutadiene (HTPB) Propellant	HTPB provides an alternative solid rocket propellant for large booster motors. This alternative could provide higher performance and power density while increasing commonality with other systems.

TA 1.1.2 Case Materials

The SOA for large human-rated segmented SRMs is the Shuttle SRB, which is a four-segment design. There have been other large-diameter motors flown that used composite cases; Titan's SRM upgrade had a 10 ft diameter. The motor cases are currently made from high-strength metal designed for reusability. Improved SRM performance is required to evolve the 70 mt SLS vehicle to a 130 mt vehicle design, which will support solar system exploration missions. Composite case designs are currently used on small 3 to 5 ft diameter monolithic SRM cases, such as the Atlas V solid strap-on motors, which are used for added thrust at lift-off. Developing manufacturing capability to replace 12 ft diameter metallic SRM case with up to a 13.4 ft diameter composite case while maintaining high reliability for human-rating, reducing recurring hardware production costs, and increasing mass fraction is one challenge. Developing large-diameter cases using composite materials presents several challenges. One is developing the manufacturing composite case membranes and joining them to metal joint rings at up to the 13.4 ft diameter. Handling and transporting large composite segments requires understanding and minimizing or eliminating handling risks. This also requires developing damage tolerance and detection methods, material tolerance limits, and quality processes.

Additive manufacturing methods such as 3D printed or freeform methods are being developed to manufacture SRM cases, domes, and joints. Currently additive manufacturing is used for small-scale hardware but scale-up to booster class is required to reduce recurring hardware costs and production schedules.

Technical Capability Objectives and Challenges

Fabrication of large (up to 13.4 ft) diameter composite motor cases and tooling requires advanced materials and processes as well as damage tolerance and detection methods for composite cases, handling methods for large composite motor cases, and manufacturing technology for the composite case membrane joined to metal joint rings for up to 13.4 ft diameter motor cases. Currently, the largest motor cases being flown, which are on Atlas V, have a 5 ft diameter. The manufacturing capability for SLS 130 mt sized large composite motor cases, which are human-rated, does not currently exist. However, there have been large composite motor cases flown, such as the three-segmented SRM upgrade, 10.5 ft diameter, on the Titan IV B, which is not currently in production and the manufacturing capability must be reconstituted. The SLS ADO is funding composite case damage tolerance work under the risk reduction program. Composite case scaling for up to 13.4 ft and joining to metallic rings are technical challenges to be addressed.

Additive manufacturing with 3D or free-form methods for fabricating large-diameter motor cases or joints is an alternate approach to composite cases. Currently only 2 ft diameter cases have been printed but larger diameter cases could be fabricated using free form electron beam fabrication. The technology challenge is the scale-up of 3D printing technology and incorporating dual material printing to create hybrid metallic or composite structures.

Benefits of Technology

Larger-diameter boosters are required to meet the performance delta-V requirement of SLS booster systems when going from 70 mt to the 130 mt SLS vehicle to meet its future mission requirements.

Table 4. TA 1.1.2 Technology Candidates – not in priority order

TA	Technology Name	Description
1.1.2.1	Manufacturing and Tooling for New 13.4 Foot Diameter Booster, Advanced Processes, New Materials	New manufacturing technologies for composite and metallic components enable large boosters while maintaining high reliability of propulsion systems and reducing recurring hardware production cost.
1.1.2.2	Composite Case Damage Tolerance and Detection Methods	This technology is designed to develop damage tolerance detection methods, material tolerance limits, and qualify processes for SLS Advanced Solid Booster.

Table 4. TA 1.1.2 Technology Candidates – not in priority order – Continued

TA	Technology Name	Description
1.1.2.3	Composite Case Membrane Integrated with Composite (Filament Wound, Pre-Preg, Molded, etc.) Joint Rings	Develop manufacturing technology for composite case membranes joined to metal joint rings on large diameter motor casings, up to 13.4 feet.
1.1.2.4	3D Printed (Additive Manufactured) Motor Case Membrane and Joint Technology	Motor case membranes and joints manufactured by a 3D printing (additive manufacturing) process to produce large-diameter solid rocket motor cases.
1.1.2.5	Low-Cost Nano-Launch Vehicle Solid Motor Casing	Low-cost SRM casing for use as propulsion for nano-launch vehicle.

TA 1.1.3 Nozzle Systems

The supersonic nozzle provides for the expansion and acceleration of hot gases and has to withstand the severe environment of high heat transfer and erosion. Technology advances in materials have allowed for mass reduction and performance improvements. The Shuttle SRB nozzle is composed of nine carbon cloth phenolic ablative liners bonded to six steel and aluminum housings. The housings are bolted together to form the structural foundation for the nozzle. The nozzle is a convergent-divergent, movable design in which an aft pivot-joint flexible bearing is the gimbal mechanism. The nozzle is gimbaled for thrust vector (direction) control. The development of a low-density, low-erosion ablative material to reduce weight in large segmented rocket motors, as well as the development of a new flex bearing that uses eroding shims instead of a flex boot for thermal protection to reduce weight and improve weight bearing capacity, are needed.

Technical Capability Objectives and Challenges

Lightweight, low-erosion nozzle materials are needed to reduce the weight of ablative nozzle materials for solid motors. Comparative erosion rates and no-ply lifting or pocketing is a performance goal. Materials are being developed for the SLS Advanced Booster. The challenge is formulating new lightweight materials that have low erosion rates and do not have ply lift or pocketing.

The SLS Advanced Booster requires a large-diameter expendable eroding shim flex bearing that does not require a flexible boot seal to protect the bearing from motor hot gasses. Eroding shims allow the flex bearing to operate throughout the burn and weigh less than the current flex boot design. The current goals for the bearing are an operating life of 130 seconds and a weight reduction of approximately 10 percent over the baseline design. A preliminary design for the SLS and process and simulation article is being built.

Benefits of Technology

Larger-diameter boosters are required to meet the performance delta-V requirement of a SLS booster system when going from 70 mt to the 130 mt SLS vehicle, to meet its future mission requirements. Weight reduction in larger-diameter SRM components is important to meeting the Advanced Booster's performance goals.

Table 5. TA 1.1.3 Technology Candidates – not in priority order

TA	Technology Name	Description
1.1.3.1	Lightweight, Low-Erosion, Materials	A low density, low erosion ablative material designed to reduce weight for large rocket motors.
1.1.3.2	Expendable Flex Bearing with Eroding Shims	Eroding shims instead of a flex boot for thermal protection for a large-scale motor.

TA 1.1.4 Hybrid Rocket Propulsion Systems

A large-scale hybrid motor stage is not being considered as an SLS option at this time, but there are a number of innovative combinations for small hybrids that will support a nano-launcher class stage. A hybrid rocket is a vehicle with a rocket motor that uses propellants in two different states of matter: one solid and the other either gas or liquid. The hybrid rocket concept can be traced back at least 75 years. In its simplest form, the rocket consists of a pressure vessel (tank) containing liquid oxidizer, a chamber containing the solid fuel, and a valve isolating the two. When thrust is desired, a suitable ignition source is introduced in the combustion chamber and the valve is opened. The liquid oxidizer (or gas) flows into the combustion chamber where it is vaporized and then reacts with the solid fuel.

Traditional methods of casting synthetic rubber and wax fuels to form solid grains can be labor intensive, requiring mold tools, and some designs incorporate extensive use of internal webbing materials to improve the grain's ability to withstand stress. Traditional hybrid propellants used are HTPB and wax. Performance can be enhanced with additives such as aluminum particles.

Current research is being conducted to take advantage of additive manufacturing, including its ability to create complex structures with unprecedented accuracy, to manufacture high-performance hybrid rocket fuel grains. It is anticipated that additive manufacturing will provide the opportunity to reduce unit production costs and improve delivery times over competing hybrid rocket motors using manual casting methods.

Current additive manufacturing work is with acrylonitrile butadiene styrene thermoplastic. Additive manufacturing may be developed to offer the ideal combination of an industrial-scale fabrication platform capable of producing large grain sections in a high modulus, chemically stable polymer with excellent accuracy and throughput. Additive manufacturing is also being used to print other hybrid motor parts, such as motor cases and domes to reduce design time and cost. The challenge is to decrease launch costs by manufacturing lower-cost SRM components. Low-cost components will provide the ability to launch on demand small satellites to an optimized orbit.

Technical Capability Objectives and Challenges

Low-cost hybrid rocket motors need to be developed for use as propulsion for launch vehicles capable of delivering nano and micro satellites (nano: 1 kg-10 kg; micro: 10 kg-100 kg) into LEO, and other possible applications. This would include a hybrid rocket motor stage for a small nano-launcher class vehicle. The capability is needed to conduct a cost-effective dedicated launch of a small satellite to a specified orbit within a reasonable time frame (hours to days) of the desired need date. Currently, small satellite launch is dependent on ride sharing with larger satellites on larger launch vehicles and is subject to the time and orbit constraints of the larger payload, often requiring waits of months to years for launch, and costing approximately three times as much per pound to orbit as for a large satellite. The current cost to launch a 100 lbm payload to LEO on a dedicated launcher is $10 million. The goal is reduce this cost to $1.5 million.

Benefits of Technology

The small satellite market is growing, requiring propulsion technology to launch the satellites. This technology will benefit NASA's Science, Research, and Technology (suborbital program) mission, the Earth Venture Suborbital mission, and Explorer missions, as well as meet potential government, universities, and commercial interest, such as providing situational awareness.

Table 6. TA 1.1.4 Technology Candidates – not in priority order

TA	Technology Name	Description
1.1.4.1	Low-Cost Nano-Launch Vehicle Hybrid Motor Stage	Low-cost hybrid rocket motors that can be used as propulsion for nano-launch vehicle.

TA 1.1.5 Fundamental Solid Propulsion Technologies

The SOA of solid rocket motor design methodology relies heavily on empirically-based tools. The methodology lacks predictive capability and is often applied with significant uncertainty to new designs, and so, requires significant levels of costly, time-consuming testing. Human-rating advanced, robust, low-cost motors will require high-fidelity, physics-based models of solid rockets to be developed for the motor propellant; internal fluid dynamic and combustion processes; complex fluid, thermal, or structural interactions; composite case, advanced liner, insulation, and nozzle materials; damage tolerance assessments; and aging and surveillance. Modeling improvements must be validated to confidently enable reduced design time, weight, and number of tests, and lead to an optimum overall design. Experimentally-derived propulsion environments are needed for validation of these tools and to provide technical understanding where analysis currently does not. Also, data acquisition and measurement technologies are needed for detailed characterization of these environments.

Technical Capability Objectives and Challenges

Provide enhancements to the development of SRMs with validated, advanced physics-based fluid dynamic, thermal, and structural modeling capabilities. Experimentally-derived propulsion environments are needed to validate these tools and provide technical understanding where analysis does not. Also, data acquisition and measurement technologies are needed for detailed characterization of these environments. Specific metrics are yet to be determined.

Benefits of Technology

Validated SRM physics-based modeling tools are vital for developing new SRM systems or incorporating advanced technology into existing systems. Such tools will reduce design cost and time, reduce the number of required tests, and provide additional insight into tests that are conducted.

Several SRM model validation efforts have been funded by other government agencies. Many of the details of the supporting technologies that facilitate the development, enhancement, and fielding of these tools for solid rocket propulsion systems are addressed in the roadmap for TA 11 (Modeling, Simulation, Information Technology, and Processing).

Table 7. TA 1.1.5 Technology Candidates – not in priority order

TA	Technology Name	Description
1.1.5.1	Physics-Based Modeling	Models that allow for simulation of solid rocket motor and structure design. They should feature tightly coupled fluid, thermal, structural, and dynamics tools for the motor propellant, internal fluid dynamic and combustion processes; complex fluid, thermal, structural interactions; composite case; advanced liners, insulation, and nozzle materials; damage tolerance assessments; and aging and surveillance studies.

TA 1.1.6 Integrated Solid Motor System

A new five-segment advanced solid rocket booster is being developed for the SLS Block 1, which provides increased thrust to meet the 70 mt payload requirement. It is derived from the Shuttle four-segment SRB. An advanced booster option for SLS Block 1b and 2 is necessary to meet the 130 mt payload requirement. This booster will require improved propellant, composite case materials instead of metal, and larger-diameter segments.

Technical Capability Objectives and Challenges

The new five-segment booster option for the SLS Block 1 provides a thrust increase of 3,300 klbf which is needed to meet the vehicle's 70 mt payload requirements. The five-segment SRB is currently in development through the SLS program and has a need date of 2017. The current technical challenges are the liner and insulation.

A new advanced, large, high-performance SRB is needed for the SLS Block 1b and 2 to meet the 130 mt payload requirement. It will incorporate technologies from TA 1.1.1 through 1.1.3, as well as 1.1.7, and will provide a thrust increase to 4,500 klbf. As referenced in the respective TA 1 areas, some technology work has already been started under the SLS ADO risk reduction program. The SRB is one of three elements being considered by SLS to achieve the 130 mt payload requirement. The need date is currently 2021.

A low-cost SRM stage must be developed for a small nano-launcher class vehicle. This vehicle will be able to conduct a cost-effective dedicated launch to a specified orbit within a reasonable time frame (hours to days) of the desired need date. The operational objective of the vehicle is to reduce launch costs for 100 lbm payload to LEO from $10 million to $1.5 million. There is also work under way to decrease launch costs through manufacturing lower-cost SRM components. The target date for supporting NASA's Science, Research, and Technology (suborbital program) mission, the Earth Venture Suborbital mission, and Explorer missions, is 2022.

Benefits of Technology

Development of the increased thrust five-segment SRB enables near-term SLS missions into the solar system for the 70 mt payload requirement for solar system missions. Flight-demonstrated technology can be used to develop the large high-performance SRB required for the 130 mt payloads. Development of the new Advanced Booster enables long-term missions such as Into the Solar System, Exploring Other Worlds, and Planetary Exploration, which require a 130 mt payload capability.

Table 8. TA 1.1.6 Technology Candidates – not in priority order

TA	Technology Name	Description
1.1.6.1	Five-Segment Advanced Solid Rocket Booster	New five-segment booster option for SLS Block 1 derived from Shuttle four-segment SRB that provides thrust increase to meet 70 mt payload requirement.
1.1.6.2	Advanced Large High Performance Solid Booster System Incorporating Subsystem Technologies from 1.1.1 to 1.1.3, and 1.1.7	New booster option for SLS Block 1b and 2 that provides thrust increase to meet 130 mt payload requirement.
1.1.6.3	Low-Cost Nano-Launch Vehicle Solid Motor Stage	Low-cost SRM for use as propulsion for nano-launch vehicle.

TA 1.1.7 Liner and Insulation

The Shuttle RSRM used asbestos as part of its insulation material, requiring a waiver for the Shuttle SRM during its last few years of operation. New systems cannot have a waiver, so new asbestos-free insulation options must be developed. Rubber insulation free of Crysotile, the most common mineral form of asbestos, had already been qualified for use on the Shuttle prior to its retirement, but was never actually used in flight. Current asbestos-free rubber insulation has experienced processing issues, which has resulted in significant rework or scrapping of large cast motor segments. The booster currently in development requires a sprayable insulating/ablative insulation/liner with insulating properties similar to fiber-filed nitrile butadiene rubber (NBR) and ethylene propylene diene monomer (EPDM) insulations to provide significant weight reduction and to eliminate the current processing issues.

Technical Capability Objectives and Challenges

SRM case liner and insulation materials that are asbestos-free and still maintain the SRM internal case temperature below the thermal limits are needed. Two approaches are in development under the SLS Booster project. The first approach uses Polybenzimidazole Acrylonitrile Butadiene Rubber (PBI NBR) based asbestos-free liner and insulation. Processing issues with PBI NBR will require additional technical development.

The second approach to replacing the existing liner is development of an asbestos-free insulating/ablative sprayable liner and insulation. This provides significant weight reduction and eliminates processing issues found in the current system. Current issues that may require further technology development remain. These technologies are needed by 2021 to support the SLS 130 mt vehicle for Extending Reach Beyond LEO, Into the Solar System, Exploring Other Worlds, and Planetary Exploration missions.

Benefits of Technology

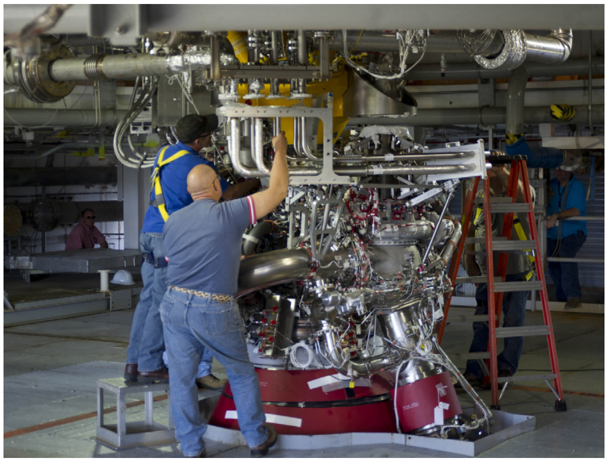
The use of PBI NBR would eliminate health issues by developing an asbestos-free liner and insulation system that still maintains the SRB internal motor case within thermal limits. This technology is required for the SLS Exploration Mission 1 (EM-1) and Exploration Mission 2 (EM-2). The objective is to develop an insulating/ablative, sprayable liner and insulation that significantly reduces weight, eliminates process issues being addressed today, and maintains the SRB internal case within temperature limits. This is required to meet the SLS 130 mt vehicle requirements.

Table 9. TA 1.1.7 Technology Candidates – not in priority order

TA	Technology Name	Description
1.1.7.1	Polybenzimidazole Acrylonitrile Butadiene Rubber (PBI NBR) Based Asbestos-Free Liner and Insulation	Reformulation of insulation using an alternative to asbestos.
1.1.7.2	Insulating/Ablative Sprayable Liner	This is a liner capable of insulative properties similar to fiber-filled NBR and EPDM insulations. Includes significant weight reduction and elimination of process issues addressed today.

TA 1.2: Liquid Rocket Propulsion Systems

The advantages of liquid rocket engines (LRE) include generally higher I_{sp} and better thrust control (including throttling and restart capability) than solids. Liquid rocket propulsion systems are more operationally complex than SRMs and require some form of active flow control that introduces additional opportunities for failures. The LRE itself is a carefully designed machine comprised of components including gas generators or preburners, turbopumps, combustion chambers, engine controllers, and flow valves. There are three predominant variants of engine thermodynamic cycles, namely the expander cycle, the gas generator cycle, and the staged combustion engine cycle. The latter is the highest performing and also the most complex and represents the SOA in LRE design. High performance, combined with high reliability and fault tolerance, are necessary attributes for LRE engines of any cycle. Further, LREs must achieve affordability through modern technologies.



J-2X LOX/LH_2 Engine Installation

Sub-Goals

The liquid propulsion roadmap addresses the critical need to improve the production and manufacturability of large booster engines—whether hydrogen-fueled or hydrocarbon-fueled (kerosene and perhaps methane as well)—in such a way as to minimize per-unit cost of an engine without sacrificing performance or reliability. Since LREs are not produced in large numbers, given limited launch vehicle flight rates, the approach must involve additively manufactured technologies and use advanced materials suitable for LRE applications.

The development of an advanced new upper stage engine—a U.S. version of the oxygen-rich staged combustion cycle engine, and potentially the first methane-fueled LRE—will ensure that current and future Earth-to-orbit launch systems will be powered by a reliable fleet of modern booster and upper stage LREs at a more affordable cost, ostensibly 25 to 50 percent lower than current costs. In turn, the future launch systems will enable exploration missions beyond Earth orbit for many decades.

The particular goals, objectives, challenges, and benefits for liquid rocket propulsion systems are highlighted in Table 10, and described in greater detail in the following sections. There are primarily two conventional fuels used in modern launch vehicle boost propulsion: LH_2 and Rocket Propellant (RP)-1. This is not expected to change within the timeframe of this roadmap. There are multiple LRE products from domestic and international suppliers for both hydrogen-fueled and kerosene-fueled. However, the discussion below is framed in the context of U.S. capability and desired advancements.

Table 10. Summary of Level 1.2 Sub-Goals, Objectives, Challenges, and Benefits

Level 1		
1.0 Launch Propulsion Systems	Goals:	Make access to space more reliable, routine, and cost effective.
Level 2		
1.2 Liquid Rocket Propulsion Systems	Sub-Goals:	Improve the production and manufacturability of large booster engines to reduce cost without sacrificing performance or reliability.
Level 3		
1.2.1 LH_2/LOX Based	Objectives:	Achieve improved production rates and reduced costs per unit through the innovative use of modern manufacturing capabilities and ongoing advancements in materials and manufacturing.
	Challenges:	Materials and manufacturing techniques.
	Benefits:	Precludes the need for the dual-engine RL10s or quadruple RL10 configurations currently envisioned for SLS upper stage thus being more cost effective. Improves production rates and costs of SLS core engines through modern manufacturing capabilities.
1.2.2 RP/LOX Based	Objectives:	Develop an ORSC cycle kerosene engine that matches or improves upon the capabilities of foreign-built equivalents and enables new advanced liquid boosters for SLS 130 mt vehicle.
	Challenges:	Manufacturing processes and materials.
	Benefits:	Reduces or eliminates the reliance on international partners for providing a critical part of a launch propulsion system, and eventually developing an ample supply of this advanced high performing kerosene engine for many decades within the domestic industrial base.
1.2.3 CH_4/LOX Based	Objectives:	Develop a low-cost LOX/CH_4 engine for nano-launch vehicles.
	Challenges:	Launch on demand.
	Benefits:	Provides a lower-cost booster system built around the relatively abundant and low-cost methane commodity, which has a noticeable I_{sp} advantage over kerosene.
1.2.4 Detonation Wave Engines - Closed Cycle	NASA is not currently advancing any technologies in this area within the timeframe of this roadmap.	
1.2.5 Propellants	Currently, no identified mission need exists to justify NASA development in alternative liquid propellants for launch.	
1.2.6 Fundamental Liquid Propulsion Technologies	Objectives:	Provide accurate physics-based predictions of a design's performance, fluid and thermal environments, structural margin, and other figures of merit to enable an expeditious DDT&E effort and lower hardware costs.
	Challenges:	Balancing the trade between model fidelity and efficiency, model validation, and integration into existing design methodologies.
	Benefits:	Reduces design cost and time, reduces the number of required tests, and provide additional insight into tests that are conducted.

TA 1.2.1 LH_2/LOX Based

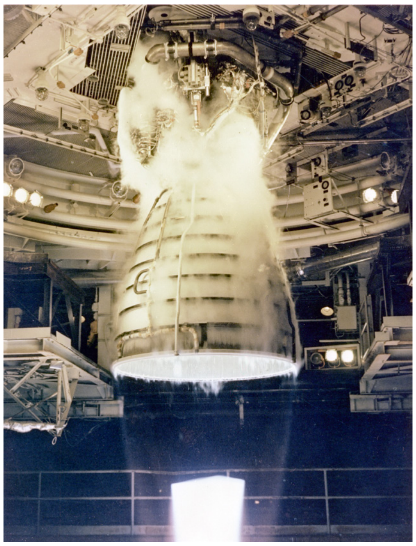
LOX/LH_2 Engine Test

Hydrogen-fueled engines are already in wide use in launch vehicle first stage and upper stage propulsion applications, frequently in multi-engine configurations, often with throttling capability and with thrust vector control by nozzle gimballing. Technology advancements and challenges for LRE applications are typically application-specific. For instance, the existing SOA reusable booster engine, the RS-25D, is being adapted from its prior usage as the Shuttle Orbiter Main Engine to future usage as the SLS RS-25 Core Stage Engine. SLS inlet pressures to the engine pump will be higher and therefore cause modifications to the engine operations. A further evolution to an RS-25 expendable version of the RS-25 engine is expected to involve modern and advanced manufacturing methods for manufacturability (production rate) and affordability gains (per unit cost) while maintaining its heritage high performance in terms of I_{sp}, which is generally 450 seconds or greater.

Similarly, for upper-stage engines, J-2X and a potential future advanced upper stage engine, the challenges will also involve manufacturability and affordability improvements in their complex precision combustion devices, with a special emphasis on materials and manufacturing of their respective high-area-ratio nozzles.

Technical Capability Objectives and Challenges

As indicated in Table 10, the primary objective is to achieve improved production rates and reduced costs per unit through the innovative use of modern manufacturing capabilities and ongoing advancements in materials and manufacturing. Whereas the RS-25D is an existing engine that is being adapted to a new application (accommodating higher inlet pressures). There is great potential for intended improvements on the RS-25 expendable version of the RS-25D reusable LRE. A goal to reduce per-unit cost of an LRE by 25 to 50 percent by 2020 is set forth, while maintaining at least its current levels of performance and reliability.



RS25 Engine Test - LOX/LH_2 Staged Combustion

Benefits of Technology

With an improved RS-25 production line, the SLS Block 1 (70 mt) and its future versions will rely on an ample domestic supply of these expendable engines for flight usage, spares, and additional risk-reduction and improvements in ground testing campaigns for future engine evolution paths. A collateral benefit is the long-term sustainment of the industrial base for LRE DDT&E and associated research and technology.

A new common upper stage will provide a single larger upper stage engine at 60,000 lbf thrust, and will thereby preclude the need for the dual-engine RL10s or quadruple RL10 configurations currently envisioned. Assuming commonality with an in-space cryogenic stage, the approach can be cost effective by avoiding a comparable parallel DDT&E effort for an in-space cryogenic stage. The potentially larger 290 klbf J-2X upper stage engine can support further Earth-to-orbit and beyond Earth orbit capability for SLS in Block 2 (130 mt).

Table 11. TA 1.2.1 Technology Candidates – not in priority order

TA	Technology Name	Description
1.2.1.1	J-2X Upper Stage Engine	The J-2X is a throttleable, liquid-fueled cryogenic rocket engine designed for upper stage use.
1.2.1.2	Space Shuttle Main Engine (RS-25D) Modified	Adaptation of Existing RS-25D engines to the SLS Core Stage for Block 1 to provide needed core stage thrust.
1.2.1.3	RS-25 Expendable Engine	Derivative RS-25 to accommodate production capabilities for reduced cost and make engine expendable without compromising on current RS-25D performance.
1.2.1.4	Common Upper Stage / In-Space Stage	Upper stage engine that can function as in-space engine for transfer stages as well as Earth-to-orbit stage.

TA 1.2.2 RP/LOX Based

Kerosene-fueled engines are also in wide use in launch vehicle first stages and occasionally upper stage propulsion applications. Unlike the hydrogen-fueled equivalents, kerosene-powered boosters are always more compact due to the order-of-magnitude higher density of the propellant, and operability is improved since kerosene is in liquid form at Earth-ambient conditions. Booster stage configurations are multi-engine and include thrust vector control by nozzle gimballing. Kerosene is hardly ever used for upper stage in the United States. The existing SOA is manifested instead in multiple LREs, most notably the foreign-designed and built heritage RD-180 and the NK-33, both utilizing ORSC with I_{sp} over 330 seconds. These foreign-made products are notably procured by U.S. domestic expendable launch vehicle providers. Domestically, the U.S. industry has only produced the simpler kerosene gas generator cycle engines (I_{sp} a little over 300 seconds) and is thus reliant on foreign countries for higher-performing ORSC versions. Technology associated with designing and producing the ORSC engines includes materials compatibility with oxygen-rich environments, along with the comparable manufacturing technologies that are also relevant to the large hydrogen-fueled engines. This type of kerosene-fueled engine is needed both for the Nation's current expendable satellite launchers, the Atlas V and Antares, and could be needed for the future evolution of the NASA crewed exploration launcher SLS (block upgrades for 105 mt and 130 mt lift capability).

Technical Capability Objectives and Challenges

As indicated in Table 10, the primary objective is to add an ORSC cycle kerosene engine to the U.S. fleet of LREs that matches or improves upon the capabilities of foreign-built equivalents. Design targets include improvements in reliability, performance, and thrust-to-weight ratio over existing products, and manufacturing technologies may enable some of those targets. Another option is a large kerosene engine based on a simpler gas generator engine cycle. Both options are extensive DDT&E efforts, given the inherent complexity of developing large LREs and the significant resources involved in building and testing such products.

At the small end of the scale of launch propulsion systems, nano-launcher class vehicle technology involves highly operable oxygen/hydrocarbon LREs that are pressure-fed instead of pump-fed devices. The hydrocarbon may be kerosene, propane, or methane and is covered separately as part of the TA 1.2.3 subsection.

Benefits of Technology

An important benefit of a new domestic RP/LOX engine would be reducing or eliminating the reliance on international partners for providing a critical part of a launch propulsion system, and eventually developing an ample supply of this advanced high performing kerosene engine for many decades within the domestic industrial base. A large ORSC engine of one million pounds thrust (or higher) is a candidate to replace SLS solid rocket boosters in its 130 mt configuration, and is thus an enabling technology for the human exploration of Mars.

Table 12. TA 1.2.2 Technology Candidates – not in priority order

TA	Technology Name	Description
1.2.2.1	Oxygen-Rich Staged Combustion (ORSC) Cycle Engine	Large ORSC cycle RP/LOX engine for use as booster propulsion.
1.2.2.2	Large F-1 Class Gas Generator (GG) Cycle Engine	Large gas generator cycle RP/LOX engine for use as booster propulsion.
1.2.2.3	Low-Cost Nano-Launch Vehicle Stage Engine (Rocket Propellant)	Low-cost pressure-fed cycle RP-1/LOX engines for use as propulsion for nano-launcher class vehicle.

TA 1.2.3 CH_4/LOX Based

There are no current launch vehicles that incorporate CH_4-fueled rocket propulsion. Both public and private sector research and development in the U.S. for CH_4-fueled LREs has been performed at subscale levels of thrust and has focused on thrust chambers and demonstrator engines as a precursor to flight engine development. There is interest in a CH_4 staged combustion engine with a relatively high I_{sp} of up to 360 seconds. As in any first-of-a-kind full-scale development of an engine and its associated flight weight operational system, there is a great deal to be learned. Whether for boost stage, or upper stage applications, characterizing the combustion stability and thermal aspects of the CH_4-based engine will be most important, followed by addressing the issues of efficient manufacturing and minimizing per-unit cost.

Technical Capability Objectives and Challenges

In the recent past, CH_4 has been successfully used in ancillary propulsion for research and technology activities and has shown promise as a candidate for a large pump-fed liquid rocket engine with an I_{sp} of greater than 360 seconds at one million pounds of thrust. A small-scale, CH_4-fueled, pressure-fed engine may be a potentially enhancing approach that allows nano-launch systems to deliver very small payloads to Earth orbit at much lower costs than larger launch systems, and enables small spacecraft to obtain a dedicated mission instead of a payload ride-share agreement.

Benefits of Technology

For Earth-to-orbit applications, there is a potential for a lower-cost booster system to be built around the relatively abundant and low-cost CH_4 commodity, which has a noticeable I_{sp} advantage over kerosene.

Table 13. TA 1.2.3 Technology Candidates – not in priority order

TA	Technology Name	Description
1.2.3.1	Low-Cost Nano-Launch Vehicle Stage Engine (Methane)	Low-cost pressure-fed cycle LOX/CH_4 engines for use as propulsion for nano-launcher class vehicle.

TA 1.2.4 Detonation Wave Engines (Closed Cycle)

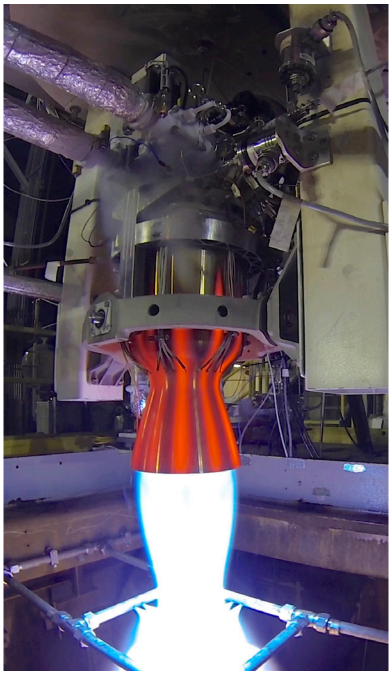
NASA is not currently advancing any technology candidates in this area within the timeframe of this roadmap.

TA 1.2.5 Propellants

Currently, no identified mission need exists to justify NASA development in alternative liquid propellants for launch. Other potential propellant alternatives fall under the definition of basic research and are not covered by this roadmap. This roadmap only covers applied research and development.

TA 1.2.6 Fundamental Liquid Propulsion Technologies

Due to the formidable up-front time and cost of new engine development, most practitioners are increasingly relying on advanced design and analysis tools to achieve and optimize technical designs that meet mission requirements. Accurate physics-based prediction of a design's component- and system-level performance, fluid and thermal environments, structural margin, and other figures of merit enable an expeditious DDT&E effort. Physics-based modeling also minimizes rework or redesign cycles and further lowers development costs. Design and analysis tools include discipline-unique tools and system-level optimization tools, as well as methods that enable more integrated design optimization and characterization. Validated modeling improvements will reduce design time, weight, the number of required tests, and lead to an optimum design. Such tools are also critical for assessing design margins that help avoid high-risk designs. Development of these tools is increasingly integral to the DDT&E process. Experimentally-derived propulsion environments are needed to validate these tools and provide technical understanding where analysis does not. Data acquisition and measurement technologies are needed for detailed characterization of these environments. Additional focused developments in integrated design and analysis that incorporate modern computer-aided design (CAD) and multi-disciplinary analysis capabilities are required to meet increasingly aggressive cost and schedule targets. Additive manufacturing techniques (e.g., CAD to prototype) hold promise to achieve a prototype product in a more efficient manner.



Additively Manufactured Liquid Rocket Chamber Nozzle

Technical Capability Objectives and Challenges

Accurate physics-based predictions of a design's performance, fluid and thermal environments, structural margin, and other figures of merit enable an expeditious DDT&E effort and lower hardware costs. Experimentally-derived propulsion environments are needed to validate these tools and provide technical understanding where analysis does not. Additionally, data acquisition and measurement technologies are needed to provide detailed characterization of these environments. Challenges include balancing the trade between model fidelity and efficiency, model validation, and integration into existing design methodologies.

Benefits of Technology

Validated LRE physics-based modeling tools are vital for developing new LRE systems or incorporating advanced technology into existing systems. Such tools will reduce design cost and time, reduce the number of required tests, and provide additional insight into tests that are conducted. Many of the details of the supporting technologies that facilitate the development, enhancement, and fielding of these tools for liquid rocket propulsion systems are addressed in TA 11 (Modeling, Simulation, Information Technology, and Processing).

Table 14. TA 1.2.6 Technology Candidates – not in priority order

TA	Technology Name	Description
1.2.6.1	Advanced Design and Analysis Tools	These fully integrated models involve tightly coupled fluid, thermal, structural/structural dynamics that accurately simulate liquid rocket engine performance, stability, fluid, thermal, and structural characteristics.
1.2.6.2	Advanced Engine Component Manufacturing	Production of advanced low-cost cryogenic and RP components through advanced materials and improved production methods.

TA 1.3: Air-Breathing Propulsion Systems

Air Breathing Propulsion for aeronautic applications is being addressed in the roadmap for TA 15 (Aeronautics). NASA is not currently advancing any technologies applicable for Earth-to-orbit in this area within the timeframe of this roadmap.

TA 1.4: Ancillary Propulsion Systems

Ancillary propulsion systems include a broad range of component types, from thrusters and valves to pressurization systems, high-pressure tanks, and feed or pressurization lines. The majority of ancillary propulsion system elements currently in use for launch propulsion have heritage technologies developed 30-40 years ago. However, high-performance elements used in missile systems have been considered recently and show promise for enhancing performance and reducing production costs. Producing complex propulsion elements (thrusters, valve bodies and parts, actuator parts, etc.) using advanced manufacturing processes could also dramatically reduce the costs and time of design and development cycles. Other activities outlined within ancillary propulsion technologies are efforts to adapt to human spaceflight, and certain elements or components already in use for expendable, commercial launch vehicles. While these efforts do not dramatically increase performance or decrease cost over the SOA for commercial cargo applications, they are intended to bring comparable utility and operational benefits while increasing the reliability and robustness of the elements, making them suitable for human spaceflight. Finally, fundamental ancillary propulsion systems consist of crosscutting technologies, and improvements of analytical modeling capabilities.

Sub-Goals

The development of low-cost cryogenic and RP valves, lines, and support components is essential to foster low-cost vehicle development and invigorate the Nation's technology base in ancillary propulsion sytems. The goal is to enhance vehicle production and improve overall vehicle reliability and safety while reducing operational costs. Some capabilities that are within reach include nontoxic reaction control systems; high-powered electromechanical actuators (EMAs) and their supporting power supply and distribution systems; large, robust mechanical separation systems; and launch abort systems with high-thrust, steerable motors tied to an adaptive flight control system. Finally, cross-cutting analytical capabilities will lower DDT&E costs by reducing the need for expensive concept testing and improving early design fidelity. The development of broadly applicable materials for propulsion systems will relax design constraints in critical applications, improving performance and design robustness. Once developed, these capabilities would have an immediate positive impact on vehicle production and operational costs, overall vehicle reliability, and ground and flight safety.

Table 15. Summary of Level 1.4 Sub-Goals, Objectives, Challenges, and Benefits

Level 1		
1.0 Launch Propulsion Systems	Goals:	Make access to space more reliable, routine, and cost effective.
Level 2		
1.4 Ancillary Propulsion Systems	Sub-Goals:	Enhance vehicle production and improve overall vehicle reliability and safety while reducing operational costs.
Level 3		
1.4.1 Auxiliary Control Systems	Objectives:	Increase performance and reduce cost through the use of advanced materials. Decrease operations and logistics costs through the development of nontoxic auxiliary control systems.
	Challenges:	Advanced production techniques, use of new materials, or simplification of logistics by eliminating toxic propellant combinations.
	Benefits:	Uses composite manufacturing technology and higher-pressure operation to maximize thrust-to-weight and reduces cost by reducing the complexity of operations and logistics. Enables desired nano-launch concepts. Optimizes geometries and systems integration through the use of additive manufacturing.
1.4.2 Main Propulsion Systems (Excluding Engines)	Objectives:	Reduce the production cost of complex, low-production-rate propulsion systems' components through the use of advanced manufacturing techniques.
	Challenges:	Developing standard acceptable procedures, and qualifying these procedures and methods to launch propulsion system applications.
	Benefits:	Produces complex, low-production-rate main propulsion system components at significantly lower cost and allows new designs that are un-producible through conventional methods.
1.4.3 Launch Abort Systems	Objectives:	Develop functional systems that meet reliability, performance, and human system integration requirements.
	Challenges:	Controllability of solid motors. Rapid initial ignition and development of main stage thrust.
	Benefits:	Improves crew safety and provides rapid, high thrust for maximum separation from a hazardous event, while maintaining control of the abort flight path. Provides launch abort functions while utilizing orbital maneuvering propellant already required by the vehicle, thus reducing required additional mass.
1.4.4 Thrust Vector Control Systems	Objectives:	Reduce cost and improve safety while meeting existing performance requirements.
	Challenges:	Adapting nontoxic or green propellants to auxiliary power unit operations. High reaction temperature and associated thermal management of the propellants.
	Benefits:	Increases performance, provides simplified overall integration, and reduces cost. Reduces cost through simplified, safer logistics, and ground operations.
1.4.5 Health Management and Sensors	While health management approaches are intrinsic to propulsion systems development, no specific technologies are addressed here.	
1.4.6 Pyro and Separation Systems	Objectives:	Develop small, very-low-cost separation systems for nano-launch.
	Challenges:	Launch on demand.
	Benefits:	Enables small-scale, low-cost separation systems.
1.4.7 Fundamental Ancillary Propulsion Technologies	Objectives:	Improve propulsion system materials to relax design constraints, increase reliability, and increase performance.
	Challenges:	Validation of analytical models especially where unsteady aspects are important.
	Benefits:	Relaxes design constraints for propulsion systems development and supports the design of significantly more robust systems. Reduces DDT&E costs and schedule by reducing dependence on expensive empirically-based designs and consequent high levels of tests.

TA 1.4.1 Auxiliary Control Systems

The SOA for U.S. auxiliary control systems (including RCS and RoCS) is generally based on technologies developed for NASA missions that occurred 30 to 40 years ago. One area for improvement includes adapting thruster technologies developed by other government agencies to NASA science and human spaceflight applications. Some of these thrusters use composite manufacturing technology and higher-pressure operation to maximize thrust-to-weight and reduce cost. Another area for improvement is related to the toxic nature of heritage nitrogen tetroxide (N_2O_4) and hydrazine propellants. Systems based on nontoxic propellants show promise to significantly reduce cost by reducing operations and logistics complexity. Finally, recent interest in nano-launch capabilities due to rapidly expanding CubeSat launch demand has created a need for very low cost, highly integrated, small reaction control systems.

Technical Capability Objectives and Challenges

The majority of capability objectives and development challenges within the Auxiliary Control Systems (ACS) area are related to decreasing costs through advanced production techniques, using new materials, or simplifying logistics by eliminating toxic propellant combinations, thereby eliminating the need for protective clothing and breathing apparatus. Adapting other thruster technologies developed by other U.S. government agencies to NASA science and human spaceflight applications will make use of advanced production methods and composite construction, but will require additional qualification testing and some significant adaptation of component and seal technology to support increased life and operations limitations. Developing systems that use nontoxic propellants will lower logistics and operations costs, but will also require scaling to greater thrust levels and understanding catalyst thermal balances. Finally, small reaction control capabilities are required for nano-launch applications. However, these systems will require a higher degree of integration or optimization than is typical for such systems to help achieve the high propellant mass fractions required to make small launch systems viable.

Benefits of Technology

Adapting other thruster technologies developed by other U.S. government agencies makes use of composite manufacturing technology and higher-pressure operation to maximize thrust-to-weight and reduce cost. Reaction control thrusters and systems on nontoxic propellants could significantly reduce cost by reducing the complexity of operations and logistics. Finally, highly-integrated, small reaction control systems enable desired nano-launch concepts.

Table 16. TA 1.4.1 Technology Candidates – not in priority order

TA	Technology Name	Description
1.4.1.1	Low-Cost, High Thrust-to-Weight Ratio 100 lbf Class Reaction Control Systems (RCS)	Develop thrusters with moderate-to-long life capability, comparable to or improved upon SOA, and lower system mass.
1.4.1.2	Nontoxic Reaction Control Propellants	Nontoxic RCS propellants can reduce ground infrastructure cost and complexity, improve ground safety and operational timelines, as well as potentially reduce flight vehicle system production costs and improve performance.
1.4.1.3	Low Cost Reaction Control System (RCS) For Small Launch (Microsat Launch Vehicle or Nano-Launcher)	This technology is designed to provide reaction control propulsion capability using commercial-off-the-shelf (COTS) or additive manufacturing components that enhance affordability and meet reduced performance and reliability requirements.

TA 1.4.2 Main Propulsion Systems

Main propulsion systems refer to the vehicle fluid systems that integrate the engine, vehicle systems, propellant tanks, and ground systems. These systems are a combination of complex components including line elements, flex ducts, valves, and actuators. The components are fairly mature and the SOA performance meets the majority of launch propulsion needs. However, recent developments in advanced manufacturing and production methods have created the opportunity to produce these components at significantly lower cost. In addition, these same manufacturing advances are allowing new designs to be considered that may have been un-producible through conventional methods.

Technical Capability Objectives and Challenges

As with ACS, the majority of capability objectives and development challenges are related to decreasing complex, low-production-rate component costs through advanced manufacturing and production techniques. These components are fairly mature and the SOA performance meets the majority of launch propulsion needs. However, recent developments in additive manufacturing and other advanced production methods have created the opportunity to produce these components at significantly lower costs. Challenges to this approach relate to developing standard acceptable procedures, and qualifying these procedures and methods to launch propulsion system applications.

Benefits of Technology

Recent developments in advanced manufacturing and production methods have created the opportunity to produce complex, low-production-rate main propulsion system components at significantly lower cost. In addition, these same manufacturing advances are allowing new designs to be considered that may have been un-producible through conventional methods.

Table 17. TA 1.4.2 Technology Candidates – not in priority order

TA	Technology Name	Description
1.4.2.1	Advanced, Low-Cost Cryogenic and Rocket Propellant Components	Production of advanced low-cost cryogenic and RP components through advanced materials and improved production methods.

TA 1.4.3 Launch Abort Systems

Operational flights demonstrating SOA for dedicated human launch abort systems in the U.S. date back to the 1970s. The Shuttle system utilized complete orbiter Return to Launch Site or Abort to Orbit operations. However, no dedicated system existed to separate the Shuttle crew from primary propulsion hazards. Current concepts for abort operations include guided attitude control motors (controllable solids), vectorable solid motors, and even liquid-based systems that utilize orbital maneuvering and reaction control propellant in case of a required abort.

Technical Capability Objectives and Challenges

Capability objectives for launch abort systems center around developing functional systems that meet reliability, performance, and human system integration requirements. Solid-based systems develop rapid, high thrust and are very capable of quickly separating the crew from hazardous launch propulsion failures. However, challenges exist in the controllability of these solid motors. In contrast, liquid systems are very controllable. Liquid engines and thrusters can be throttled and pulsed, and thrust can be distributed across many thrusters to provide control of vehicle trajectory. However, as initial abort thrust requirements grow, the rapid initial ignition and development of main stage thrust can be a challenge. In addition, low-cost flight termination systems for nano-launch are required. These systems must meet stringent range safety requirements while achieving extremely low cost.

Benefits of Technology

New launch abort systems are required for crew safety. Vectorable and controllable solids have the benefits of rapid, high thrust for maximum separation from a hazardous event, while maintaining control of the abort flight path. Easily controllable, liquid-based systems can provide launch abort functions while utilizing orbital maneuvering propellant already required by the vehicle, thus reducing required additional mass.

Table 18. TA 1.4.3 Technology Candidates – not in priority order

TA	Technology Name	Description
1.4.3.1	Vectorable High-Thrust Abort Motor	This technology incorporates low-cost, highly maneuverable thrust vector control systems used in large SRMs.
1.4.3.2	Integrated Liquid Propulsion Bi-Propellant Ascent Abort System	Integrated propulsion systems that employ liquid propellants capable of providing both the high thrust required for vehicle abort and low thrust required for on-orbit maneuvering and attitude control.
1.4.3.3	Solid Propellant Thrust Termination/Abort System	This technology provides low-cost thrust termination and safe ascent abort system for launch vehicles.

TA 1.4.4 Thrust Vector Control Systems

With the exception of relatively small commercial expendable upper stage TVC, the SOA for U.S. launch vehicles employs hydraulic actuators, typically powered by hydrazine-driven auxiliary power units (APUs). The toxic propellant used in these APUs pose similar operations and logistics complexities to the toxic ACS. Therefore, there is significant interest in reducing costs by developing nontoxic APUs. Similar to ACS applications, toxic propellants would be replaced by nontoxic options. There is also interest in replacing more complicated hydraulic actuators with large EMAs or electro-hydraulic actuators (EHAs).

Technical Capability Objectives and Challenges

The primary capability objectives and challenges for TVC systems relate to cost reduction and improved safety, while meeting or exceeding existing performance requirements. Nontoxic-propellant-based APUs will reduce costs associated with logistics and operations by eliminating some operational hazards. However, technical challenges exist related to adapting nontoxic or green propellants to APU operations. Primary technical challenges are likely due to the high reaction temperature and associated thermal management of the propellants. There is also interest in replacing more complicated hydraulic actuators with large EMAs or EHAs. These types of actuators show the promise of increased performance, better overall integration, and reduced cost. Aside from developing the EMA, technical challenges exist in developing power systems as well. Corona proof rapid discharge batteries and power distribution systems will be required to power EMAs and EHAs in practical launch vehicle applications.

Benefits of Technology

EMAs and EHAs will likely increase performance, provide simplified overall integration, and reduce cost. However, these technologies require significant high power electric supplies. For more typical hydraulic based systems, nontoxic APU development will reduce cost through simplified, safer logistics, and ground operations.

Table 19. TA 1.4.4 Technology Candidates – not in priority order

TA	Technology Name	Description
1.4.4.1	Nontoxic Propellant-Driven Turbine-Based Auxiliary Power Units	Replacement for hydrazine-driven hydraulic power units using either nontoxic propellant or a blow-down type system.
1.4.4.2	Advanced Actuator and Controller Development (Electro-Hydraulic Actuator, Electromechanical Actuator, Integrated Actuator Package)	This is a low-cost actuator system for an integrated TVC system.
1.4.4.3	Corona-Proof, Rapid Charge/ Discharge High Power Battery and Power Distribution Systems	Limiting factor for EMA usage on larger systems is the power management system. Seek to utilize developments in battery and regeneration systems to enable power management for new actuator systems.

TA 1.4.5 Health Management and Sensors

Requirements for health management algorithm development and sensors will be derived from efforts to develop liquid engine and solid motor systems technology. While health management approaches are intrinsic to propulsion systems development, no specific technology candidates are addressed here.

TA 1.4.6 Pyro and Separation Systems

The SOA for pyro and separation systems is represented by systems used by the commercial expendable launch vehicles (ELVs). While these systems have been available and in use for decades, the criticality of these functions in human spaceflight and understanding the operation of large-scale systems have caused NASA to initiate an in-depth, frangible joint investigation and demonstration effort. No specific, large-scale hardware technologies are identified in this section. However, Section 1.4.7 describes the comprehensive analytical tools that must be developed to enable this capability.

Technical Capability Objectives and Challenges

While large-scale separation system hardware technologies requirements have not been identified, recent interest in developing a low-cost nano-launch capability has created a need for small, very-low-cost separation systems. The closest SOA for these types of applications is the analogous system used in sounding rockets. Challenges for nano-launch applications will be to produce suitable separation systems for very low cost.

Benefits of Technology

Increased demand for small and CubeSat launches, and the evolution of these systems to include pressurized volumes and propulsion capability (creating hazards to primary payloads) has created the need for dedicated nano-launch capabilities. One enabler of these launch capabilities is advanced small-scale, low-cost separation systems. Small-scale separation systems used for sounding rocket applications can be built upon, adapted, and simplified for nano-launch.

Table 20. TA 1.4.6 Technology Candidates – not in priority order

TA	Technology Name	Description
1.4.6.1	Low-Cost Separation Systems for Nano-Launch Vehicle Systems	This technology provide separation using COTS or additive manufacturing components that enhance affordability and meet reduced performance and reliability requirements.

TA 1.4.7 Fundamental Ancillary Propulsion Technologies

Improvements are required in advanced design tools and manufacturing technologies that support ancillary propulsion system design, development, and production to decrease the costs and time associated with DDT&E. Experimentally-derived propulsion environments are needed to validate design tools and to provide technical understanding where analysis does not. Additionally, data acquisition and measurement technologies are needed for detailed characterization of these environments.

Technical Capability Objectives and Challenges

Across all applications, general improvements in materials utilized in propulsion systems can relax design constraints, increase reliability, and increase performance. Once the advanced propulsion system type and the most beneficial material advancement approach are determined, challenges will remain in identifying the optimal area for development. Advancements in analytical design capabilities are needed to both reduce DDT&E costs and associated schedules. These tools can minimize expensive tests and will reduce reliance on empirically-based methods. Challenges with new analytical techniques include model validation, especially where unsteady aspects are important. Validation is key to establishing credibility and acceptability for specific applications.

Benefits of Technology

Advances in material properties and performance can both relax design constraints for propulsion systems development, and ultimately support the design of significantly more robust systems. Physics-based design tools and methodologies will reduce DDT&E costs and schedule by reducing dependence on expensive empirically-based designs and consequent high levels of tests.

Requirements for advancements in material technology should be developed through systems-level propulsion efforts (e.g., liquid engine, solid motor, and auxiliary propulsion systems development), and funding for appropriate technology development within TA 12 (Materials, Structures, Mechanical Systems, and Manufacturing) is needed. The appropriate development approach for integrating physics-based modeling and executing tool development and verification activities should be determined.

Details of the supporting technology that facilitate the development, enhancement, and fielding of these tools for solid rocket propulsion systems are addressed in the roadmap for TA 11 (Modeling, Simulation, Information Technology, and Processing).

Table 21. TA 1.4.7 Technology Candidates – not in priority order

TA	Technology Name	Description
1.4.7.1	Advanced Materials for Propulsion Applications	Advancements in materials can be used in a variety of propulsion system technology applications.
1.4.7.2	Comprehensive Pyrotechnic Component Modeling Tool	An integrated, physics-based comprehensive analytical tool capable of directly supporting design and analysis activities for pyrotechnic.
1.4.7.3	Physics-Based Modeling for Ancillary Propulsion Systems	Support development of auxiliary control, main propulsion, launch abort, and thrust vector control systems.

TA 1.5: Unconventional and Other Propulsion Systems

With the exception of air launch and drop systems, which have options supporting the emerging capability for nano and small satellite deployment, the SOA for technologies for unconventional and other propulsion systems is below the level being addressed in this revision of the roadmap, or NASA is not currently advancing any technologies applicable to Earth-to-orbit in this area within the timeframe of this roadmap.

Sub-Goals

Currently, small satellite launch is dependent on ride shares on large vehicles and are subject to time and orbit constraints. The current cost to launch a 100 lbm payload to LEO is $10 million. The goal for a low-cost small satellite launch system is to lower that cost to $1.5 million. This will be achieved by manufacturing low-cost propulsion hardware and innovative operations concepts, such as those promised by an air launch and drop system. The nano-launcher class work supports NASA's Science, Research, and Technology (suborbital program) mission, the Earth Venture Suborbital mission, and Explorer missions. It also supports other government agencies' need to launch small satellites to provide situational awareness.

Table 22. Summary of Level 1.5 Sub-Goals, Objectives, Challenges, and Benefits

Level 1		
1.0 Launch Propulsion Systems	Goals:	Make access to space more reliable, routine, and cost effective.
Level 2		
1.5 Unconventional and Other Propulsion Systems	Sub-Goals:	Provide affordable launch-on-demand capability.
Level 3		
1.5.1 Ground Launch Assist	No NASA mission need exists to justify NASA development within the next 20 years.	
1.5.2 Air Launch and Drop Systems	Objectives:	Provide a cost-effective, dedicated launch capability to a specified orbit within a reasonable time frame for small or nano-launcher class vehicles.
	Challenges:	Launch on demand.
	Benefits:	Reduces launch costs through hardware integration, operations, and range safety.
1.5.3 Space Tether Assist	Space Tether Assist technologies for Earth-to-orbit applications are addressed in the roadmap for TA 2 (In-Space Propulsion Technologies).	
1.5.4 Beamed Energy and Energy Addition	No NASA mission need exists to justify NASA development within the next 20 years.	
1.5.5 Nuclear	No NASA mission need exists to justify NASA development within the next 20 years.	
1.5.6 High Energy Density Materials and Propellants	No NASA mission need exists to justify NASA development within the next 20 years.	

TA 1.5.1 Ground Launch Assist

No NASA mission need exists to justify NASA development before 2035. This TABS area is out of scope with the current Agency DRMs as provided to the roadmap teams during roadmap development.

TA 1.5.2 Air Launch and Drop Systems

Nano and small satellites currently depend on getting rides as secondary payloads on conventional launch vehicles because a low-cost, dedicated launch system does not currently exist. This dependence on ridesharing means that the satellites often have to compromise on the final orbits in which they are placed, resulting in a compromise on the intended objectives. Additional safety constraints placed on secondary payloads by the primary payload may also limit whether a satellite can even get a ride.

Technical Capability Objectives and Challenges

A low-cost, air-launch system needs to be developed for a small nano-launcher class vehicle. The ability to conduct a cost-effective, dedicated launch to a specified orbit within a reasonable time frame (hours to days) of the desired need date is required. Launch costs need to be reduced from $10 million to $1.5 million for a 100 lbm payload to LEO. Launch costs also need to be decreased by manufacturing lower-cost solid rocket motor components. The target date for supporting NASA's Science, Research, and Technology (suborbital program) mission, the Earth Venture Suborbital mission, and Explorer missions is 2022.

Benefits of Technology

A low-cost, dedicated launch capability can have a significant impact on the emerging nano and small satellite market within NASA's scientific community, other government agencies, and the commercial and academic community. A concept that uses the mature technology for towed gliders as a launch platform addresses some of the more difficult cost categories impacting launch costs: hardware integration, operations, and range safety. Several current efforts are addressing the specific launch vehicle propulsion and structures costs, but even if these were "free," significant costs from the hardware integration with launch systems, ground operations, and range safety remain, which make the total costs of using a dedicated launcher prohibitive. The towed approach addresses these last categories by attempting to simplify integration and operations and removing range safety concerns entirely.

Table 23. TA 1.5.2 Technology Candidates – not in priority order

TA	Technology Name	Description
1.5.2.1	Towed Glider Air Launch System	This is an air launch system that uses a remotely/autonomously piloted glider to carry a small launch vehicle to altitude and near-vertical orientation for launch without use of a traditional launch range. The glider and launch vehicle are towed to altitude by a minimally modified existing aircraft and released from tow prior to launch.

TA 1.5.3 Space Tether Assist

Space Tether Assist technology candidates for Earth-to-orbit applications are addressed in the roadmap for TA 2 (In-Space Propulsion Technologies).

TA 1.5.4 Beamed Energy and Energy Addition

No NASA mission need exists to justify NASA development before 2035. This TABS area is out of scope with the current Agency DRMs provided to the roadmap teams during roadmap development.

TA 1.5.5 Nuclear

No NASA mission need exists to justify NASA development before 2035. This TABS area is out of scope with the current Agency DRMs provided to the roadmap teams during roadmap development. While nuclear thermal propulsion systems have been tested for applications in space, the required thrust-to-weight of the engine system needed for Earth-to-orbit has not been tested. The needed thrust-to-weight is an order of magnitude greater than that currently envisioned for nuclear systems.

TA 1.5.6 High Energy Density Materials and Propellants

No NASA mission need exists to justify NASA development within the next 20 years. This TABS area is out of scope with the current Agency DRMs provided to the roadmap teams during roadmap development.

TA 1.6: Balloon Systems

The NASA Balloon Program provides balloon launch vehicles, launch services, and ground and flight support systems to enable scientific investigations at near-space altitudes. The current zero-pressure type balloons, which are vented with zero differential pressure at the base of the balloon, provide reliable heavy-lift capabilities, but are susceptible to altitude and gas loss when flying during nighttime. Currently-used support systems are based on standard materials and heritage flight hardware that have not fully taken advantage of advances in manufacturing processes, materials, and electronics.

Sub-Goals

For balloon launch systems, new vehicles and support components need to be developed to enhance the NASA Balloon Program support capability. Enabling technologies, including the new SPBs, trajectory control, static launch systems, and floatation systems will allow new types of balloon payloads to be flown for longer durations and produce greater science returns. Other enhancing technologies will increase the support capabilities for science users, allowing more mass, power, and data to be provided to scientific instruments aboard balloon payloads.

Table 24. Summary of Level 1.6 Sub-Goals, Objectives, Challenges, and Benefits

Level 1		
1.0 Launch Propulsion Systems	Goals:	Make access to space more reliable, routine, and cost effective.
Level 2		
1.6 Balloon Launch Systems	Sub-Goals:	Develop new vehicles and support components to enhance balloon launch systems.
Level 3		
1.6.1 Super-Pressure Balloon	Objectives:	Extend balloon flight mission durations.
	Challenges:	Materials, analysis, and construction.
	Benefits:	Provides extended float durations for large scientific payloads up to 100 days. Allows polar flights at a stable float altitude.
1.6.2 Materials	Objectives:	Increase scientific instrument mass capability.
	Challenges:	Acquisition and implementation of higher mass to strength ratio materials into existing mechanical subsystems.
	Benefits:	Increases available mass for science flight equipment.
1.6.3 Pointing Systems	Objectives:	Increase pointing accuracy and stability of balloon scientific instruments.
	Challenges:	Determining the optimum size of the system that can support the widest range of instruments without requiring an excessive amount of mass, and providing the required level of performance without using spaceflight hardware.
	Benefits:	Enables advanced exoplanet, planetary, and Earth science missions on balloon platforms without the science user being responsible for developing and providing the precision pointing system.
1.6.4 Telemetry Systems	Objectives:	Increase scientific data downlink capability.
	Challenges:	Power requirements.
	Benefits:	Allows better assess to the performance of science instruments during a mission. Allows downlink of all science data, which eliminates the requirement to physically recover the onboard data storage system.

Table 24. Summary of Level 1.6 Sub-Goals, Objectives, Challenges, and Benefits - Continued

Level 3		
1.6.5 Balloon Trajectory Control	Objectives:	Provide trajectory control.
	Challenges:	Difficult environment in the stratosphere.
	Benefits:	Allows avoidance of flying over populated areas, as well as guide systems to safe termination areas at the end of the flight.
1.6.6 Power Systems	Objectives:	Increase power generation and storage.
	Challenges:	Design, manufacturing, and analysis of electronic and mechanical systems.
	Benefits:	Enables high-power scientific instruments on balloon payloads.
1.6.7 Mechanical Systems - Launch Systems	Objectives:	Remotely launch hazardous payloads while enhancing safety of launch operations.
	Challenges:	Height of launch tower, boom movement, and flight train.
	Benefits:	Enables more hazardous payloads to be launched and enhances the safety of launch operations.
1.6.8 Mechanical Systems - Parachute	Objectives:	Protect parachutes from ultraviolet (UV) rays during extended missions.
	Challenges:	Design, manufacturing, and analysis of materials.
	Benefits:	Enables extended-duration balloon missions without changing the parachute design to a stronger material.
1.6.9 Mechanical Systems - Flotation	Objectives:	Provide floatation for payloads for durations of up to several weeks in salt water.
	Challenges:	Design, manufacturing, and analysis of electronic and mechanical systems.
	Benefits:	Allows scientific payloads that require recovery to be flown on extended-duration missions that travel over ocean regions for long periods of time.

TA 1.6.1 Super-Pressure Balloon

Current NASA scientific balloon vehicles are vented designs with zero differential pressure at the base of the balloon. SPBs allow longer flight durations and minimize altitude loss during nighttime conditions. These balloons enhance existing science support capabilities.

SPB development is ongoing. One flight of the 18.8 million cubic foot design has been completed, with several more planned for the near future. The larger, higher-altitude balloon, with a volume of approximately 26 million cubic foot, has not been completely designed, built, or tested.

Super-Pressure Balloon afloat

Technical Capability Objectives and Challenges

The technical capabilities desired for the SPB include stratospheric balloon vehicles that can support (1) flight durations of up to 100 days, (2) lift capabilities of greater than 2,200 kg up to over 33 kilometers (km) and greater than 1,800 kg to over 35 km, and (3) the ability to remain at float at mid-latitudes during diurnal cycles. Current zero pressure balloons have these lift and altitude capabilities, but can only achieve extended durations at the polar regions, where constant sunlight is available. SPBs require advanced materials, analytic methods, construction, and test techniques. SPB development is currently being performed by the NASA Balloon Program, with the lower-altitude 18.8 million cubic foot balloon planned to be operational in 2015. The higher-altitude balloon has not been fabricated or test flown.

Benefits of Technology

Mid-latitude flight durations are limited due to the altitude variations exhibited by zero pressure balloons. The SPB will provide extended float durations for large scientific payloads up to 100 days. In addition, the SPB will allow for polar flights at a stable float altitude.

Table 25. TA 1.6.1 Technology Candidates – not in priority order

TA	Technology Name	Description
1.6.1.1	Extended Duration Super-Pressure Balloon (SPB)	This is a SPB with a volume of 18.8 million cubic feet.
1.6.1.2	Higher-Altitude Extended Duration Super-Pressure Balloon (SPB)	This is a SPB with a volume of 26 million cubic feet.

TA 1.6.2 Materials

Current balloon payloads and flight trains use conventional steel and aluminum materials for mechanical structures and assemblies. Lighter-weight materials would enhance the available mass for science instruments on balloon gondolas.

Technical Capability Objectives and Challenges

The technical capabilities desired for materials development include a lighter-weight gondola and flight train systems that do not compromise strength or safety factors. Development challenges include finding materials with higher strength-to-mass ratios that are not cost prohibitive to acquire or implement into existing mechanical subsystems.

Benefits of Technology

The benefit to future balloon missions is the increase in available mass for science flight equipment.

Table 26. TA 1.6.2 Technology Candidates – not in priority order

TA	Technology Name	Description
1.6.2.1	Lightweight Gondola and Flight Train Systems	Reduced mass of flight train components, including gondolas and cable ladders.

TA 1.6.3 Pointing System

Balloon-borne scientific instruments that require precision pointing have previously relied on unique pointing systems provided by the instrument team. The only available standard system provides azimuth pointing with an accuracy of approximately two degrees. A standardized, high-precision pointing system that can position scientific instruments with masses up to 700 kg within one arc second of accuracy and stability is needed.

Wallops Arc Second Pointing System (WASP)

Technical Capability Objectives and Challenges

The technical capabilities desired for the pointing system include the ability to point large scientific instruments with a mass of over 600 kg with an accuracy and stability of approximately one arc second. The system is intended to be reusable in order to support multiple flights and instrument configurations without the need for significant redesign. Development challenges include determining the optimum size of the system that can support the widest range of instruments without requiring an excessive amount of mass, and providing the required level of performance without using spaceflight hardware, which is cost prohibitive.

Benefits of Technology

The pointing system will enable advanced exoplanet, planetary, and Earth science missions on balloon platforms without the science user being responsible for developing and providing the precision pointing system.

Table 27. TA 1.6.3 Technology Candidates – not in priority order

TA	Technology Name	Description
1.6.3.1	Arc Second Balloon Pointing Systems	The Wallops Arc Second Pointing (WASP) system is used for fine pointing of large balloon science instruments.

TA 1.6.4 Telemetry Systems

Balloon science users typically collect more scientific data than can be downloaded in real time during flight. The current telemetry capability provides approximately 150 kbps using satellite relay. A higher downlink bit rate enhances science data downlink throughput during flight.

Technical Capability Objectives and Challenges

Balloon science users typically collect more scientific data than can be downloaded in real time during flight. The current telemetry capability provides approximately 100 to 150 kbps, depending on the satellite services used. Capability objectives include increasing the real-time downlink bit rate to over 400 kbps.

Benefits of Technology

Increased downlink bit rates for science data allow science users to better assess the performance of science instruments during the mission. For some users, the higher bit rates allow downlink of all science data, which eliminates the requirement to physically recover the onboard data storage system.

Table 28. TA 1.6.4 Technology Candidates – not in priority order

TA	Technology Name	Description
1.6.4.1	Balloon Telemetry Systems	Telemetry systems improve data download speeds and overall quantity.

TA 1.6.5 Balloon Trajectory Control

Longer-duration flights could be enhanced by modifying the free-floating balloon’s trajectory. Trajectory control would allow a balloon to avoid overflight of populated areas and guide systems to safe termination areas at the end of the flight.

Technical Capability Objectives and Challenges

Cross track influence of approximately 1 meter per second (m/s) over duration can allow a mid-latitude balloon flight to avoid populated areas, steer around bad storms, and guide payloads to specific locations where termination and recovery are highly probable.

Benefits of Technology

Longer-duration flights could be enhanced by modifying the free-floating balloon’s trajectory. Moderate trajectory control would allow a balloon to avoid flying over populated areas, as well as guide systems to safe termination areas at the end of the flight.

Table 29. TA 1.6.5 Technology Candidates – not in priority order

TA	Technology Name	Description
1.6.5.1	Balloon Trajectory Control System	Cross track influence of approximately 1 m/s over duration that allows a mid-latitude balloon flight to avoid populated areas, steer around bad storms, and guide payloads to specific locations where termination and recovery is highly probable.

TA 1.6.6 Power Systems

Science users require power systems with more capability for higher-power science instruments. Advancements are needed in power generation and power storage for nighttime exposure.

Technical Capability Objectives and Challenges

Science users require higher-power systems to sustain science payloads as well as handle potentially long nighttime exposures. Up to 2,000 watts of power generation and up to 24,000 watt hours of power storage are desired, with higher power-to-mass ratios than existing systems.

Benefits of Technology

Higher power generation and storage capacity enable high-power scientific instruments on balloon payloads.

Table 30. TA 1.6.6 Technology Candidates – not in priority order

TA	Technology Name	Description
1.6.6.1	Balloon Power Systems	Science users require higher power systems to power science payloads as well as the potential for power systems that can handle long nighttime exposures.

1.6.7 Mechanical Systems – Launch Systems

The current NASA scientific balloon launch systems are manually operated in close proximity to the launch vehicle and payload systems. Launch systems that can be operated remotely enable payload users to launch more hazardous payloads and enhance the safety of launch operations.

Launch tower

Technical Capability Objectives and Challenges

Some users want to launch large, hazardous payloads (e.g., rocket motors) using standard NASA balloons. The safety of personnel, equipment, and infrastructure are paramount, and a launch system that can be operated remotely is required for these special launches. The ability to remotely launch balloon payloads of over 3,600 kg with no personnel within 152 meters of the launch tower is desired.

Benefits of Technology

Launch systems that can be operated remotely enable more hazardous payloads to be launched and enhance the safety of launch operations.

Table 31. TA 1.6.7 Technology Candidates – not in priority order

TA	Technology Name	Description
1.6.7.1	Low Density Supersonic Decelerator (LDSD) Static Launch Tower	A launch system that can be operated by people remotely is required for large hazardous payload (like rocket motor) launches. Safety of personnel, equipment, and infrastructure are paramount.

TA 1.6.8 Mechanical Systems – Parachute

The current NASA scientific balloon parachutes consist of nylon, which is susceptible to ultraviolet (UV) degradation. UV protection systems would enhance the duration of balloon missions.

Technical Capability Objectives and Challenges

The technology capability objective is to develop a coating for standard NASA balloon parachutes that will provide UV ray protection and maintain the strength of the parachute material during extended duration balloon missions.

Benefits of Technology

Current balloon parachutes are constructed of nylon, which degrades with exposure to UV rays. A protective coating on the parachute would enable extended-duration balloon missions without changing the parachute design to a stronger material.

Table 32. TA 1.6.8 Technology Candidates – not in priority order

TA	Technology Name	Description
1.6.8.1	Ultraviolet Protection for Parachutes	Provide ultraviolet (UV) protection for parachutes designed for ultra-long-duration flights.

TA 1.6.9 Mechanical Systems – Flotation

Longer-duration balloon flights in mid latitudes will spend long periods over the southern oceans. There is a potential for termination over the ocean, and payload flotation is desired so the payload systems can be recovered.

Technical Capability Objectives and Challenges

Longer-duration flights in mid latitudes will spend long periods over the southern oceans. There the potential that these flights could be terminated over the ocean, and payload flotation is desired so they can be recovered. The ability to provide floatation for payloads with masses up to 3,630 kg for durations of up to several weeks in salt water is desired.

Benefits of Technology

This technology would allow scientific payloads that require recovery to be flown on extended-duration missions that travel over ocean regions for long periods of time.

Table 33. TA 1.6.9 Technology Candidates – not in priority order

TA	Technology Name	Description
1.6.9.1	Mechanical Systems: Floatation for Balloon Payloads	Payload floatation to accomplish recovery of longer-duration flights in mid-latitudes.

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Appendix

Acronyms

3D	Three Dimensional
ACS	Auxiliary Control System
ADO	Advanced Development Office
APU	Auxiliary Power Unit
CAD	Computer-Aided Design
COTS	Commercial-Off-The-Shelf
DDT&E	Design, Development, Test, and Evaluation
DRA	Design Reference Architecture
DRM	Design Reference Mission
EHA	Electro-Hydraulic Actuator
ELV	Expendable Launch Vehicle
EM	Exploration Mission
EMA	ElectroMechanical Actuator
EPDM	Ethylene Propylene Diene Monomer
GG	Gas Generator
HTPB	Hydroxyl Terminated PolyButadiene
IAP	Integrated Actuator Package
LDSD	Low Density Supersonic Decelerator
LEO	Low-Earth Orbit
LRE	Liquid Rocket Engine
NASA	National Aeronautics and Space Administration
NBR	Nitrile Butadiene Rubber
OCT	Office of the Chief Technologist
ORSC	Oxygen-Rich Staged Combustion
PBAN	Polybutadiene Acrylic Acid Acrylonitrile Prepolymer
PBI	Polybenzimidazole
PBI NBR	Polybenzimidazole Acrylonitrile Butadiene Rubber
RCS	Reaction Control System
RoCS	Roll Control System
RP	Rocket Propellant (Hydrocarbon-Based/Kerosene)
RSRM	Reusable Solid Rocket Motor
SLS	Space Launch System
SOA	State Of the Art
SPB	Super-Pressure Balloon
SRB	Solid Rocket Booster
SRM	Solid Rocket Motors
STIP	Strategic Technology Investment Plan

TA	Technology Area
TABS	Technology Area Breakdown Structure
TDRSS	Tracking and Data Relay Satellite System
TRL	Technology Readiness Level
TVC	Thrust Vector Control
U.S.	United States
UV	UltraViolet
WASP	Wallops Arc Second Pointing system
ZPB	Zero Pressure Balloon

Abbreviations and Units

Abbreviation	Definition
°R	Degrees Rankine
bps	Bits per second
CH_4	Methane
f	Force
ft	Foot/feet
h	Hour
I_{sp}	Specific impulse
kbps	Kilobytes per second
kg	Kilograms
klbf	Thousand pounds of thrust (1,000 lbs-force)
km	Kilometers
lb	Pound
lbf	Pound-force
lbm	Pound-mass
lbm/in^3	Pound-mass per cubic inch
LH_2	Liquid hydrogen
LOX	Liquid oxygen
LOX/LH	Liquid oxygen/liquid hydrogen
LOX/RP	Liquid oxygen/rocket propellant
m	Meters
M	Million
m/s	Meters per second
MCF	Million cubic foot
ms	Milliseconds
mt	Metric ton
N_2O_4	Dinitrogen tetroxide
s	Second
t	Tonne
V	Velocity
W	Watts
yr	Year

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Technology Candidate Snapshots

1.1 Solid Rocket Propulsion Systems
1.1.1 Propellants

1.1.1.1 Hydroxyl Terminated PolyButadiene (HTPB) Propellant

TECHNOLOGY

Technology Description: Hydroxyl terminated polybutadiene (HTPB) provides an alternative solid rocket propellant for large booster motors. This alternative could provide higher performance and power density while increasing commonality with other systems.

Technology Challenge: Scaling use of HTPB for large reusable solid rocket motor (RSRM)-sized booster.

Technology State of the Art: HTPB is currently used in smaller solid missile and motor applications.

Parameter, Value:
I_{sp}: 265-268 seconds;
Propellant density: 0.68 lbm/in^3

TRL 7

Technology Performance Goal: Increase specific impulse (I_{sp}) and propellant density over the state of the art.

Parameter, Value:
I_{sp}: 265-300 seconds;
Propellant density: 0.68 lbm/in^3

TRL 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Alternative high performance, high power density solid propellant.

Capability Description: Change from polybutadiene acrylic acid acrylonitrile prepolymer (PBAN) to an HTPB-type propellant for increased performance and power density. This is one element of three booster options Space Launch System (SLS) is trading for achieving the 130 mt capability.

Capability State of the Art: Shuttle RSRM and initial SLS Booster using PBAN, and other applications using HTPB in smaller missiles and tactical systems.

Parameter, Value:
I_{sp}: 267 seconds;
Propellant density: ≤ 0.68 lbm/in^3

Capability Performance Goal: Increase I_{sp} and propellant density over current capability.

Parameter, Value:
I_{sp}: 265-300 seconds;
Propellant density: > 0.68 lbm/in^3

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

1.1 Solid Rocket Propulsion Systems
1.1.2 Case Materials

1.1.2.1 Manufacturing and Tooling for New 13.4 Foot Diameter Booster, Advanced Processes, New Materials

TECHNOLOGY

Technology Description: New manufacturing technologies for composite and metallic components enable large boosters while maintaining high reliability of propulsion systems and reducing recurring hardware production cost.

Technology Challenge: Manufacturing technologies for larger boosters do not currently exist.

Technology State of the Art: Manufacturing technologies for small-diameter composite cases.

Parameter, Value:	TRL
Diameter of composite cases: 3-5 feet	3

Technology Performance Goal: Produce solid booster motor casings with a diameters of 13.4 feet.

Parameter, Value:	TRL
Diameter: 13.4 feet	9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: New manufacturing techniques and tooling for 13.4 foot diameter booster, advanced processes, and new materials.

Capability Description: Manufacture of composite and metallic components for large boosters while maintaining high reliability of propulsion systems and reducing recurring hardware production cost. This is one element of three booster options Space Launch System (SLS) is trading for achieving the 130 mt capability.

Capability State of the Art: Shuttle reusable solid rocket motor (RSRM) 12.2 foot diameter metallic cases and Graphite Epoxy Motors 3.3-5 foot diameter composite cases.

Parameter, Value:

Booster casing diameter (metallic): 12.2 feet;

Booster casing diameter (composite): 3.3-5 feet

Capability Performance Goal: Booster diameter needs to be increased to meet performance delta-V requirements of SLS booster system design.

Parameter, Value:

Large booster casing diameter: 13.4 feet

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

1.1 Solid Rocket Propulsion Systems
1.1.2 Case Materials

1.1.2.2 Composite Case Damage Tolerance and Detection Methods

TECHNOLOGY

Technology Description: Damage tolerance detection methods, material tolerance limits, and qualify processes for the Space Launch System (SLS) Advanced Solid Booster.

Technology Challenge: Detecting structural damage in the fiber structure of composite cases.

Technology State of the Art: Various high fidelity nondestructive evaluation (NDE) techniques are being used to examine many large-scale composite projects.

Parameter, Value:	**TRL**
Typically NDE techniques are capable of detecting 1 inch subsurface damage.	3

Technology Performance Goal: Develop high-speed/high-fidelity inspection technologies capable of finding Critical Initial Flaw sizes as defined by damage tolerance.

Parameter, Value:	**TRL**
Critical initial flaw is dependent on motor case thickness and operating pressure.	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: New composite case damage tolerance detection methods are required.

Capability Description: Develop damage tolerance detection methods, material tolerance limits, and qualify processes for SLS Advanced Solid Booster. This is one element of three booster options SLS is trading for achieving the 130 mt capability.

Capability State of the Art: Automated ultrasound is used to inspect large-scale payload fairings for Delta IV.

Parameter, Value:

Current NDE capabilities include detection of manufacturing flaws and potential damage caused by handling.

Capability Performance Goal: Develop the capability to detect all manufacturing flaws and their potential impacts.

Parameter, Value:

NDE capability parameters will be defined by design.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

1.1 Solid Rocket Propulsion Systems
1.1.2 Case Materials

1.1.2.3 Composite Case Membrane Integrated with Composite (Filament Wound, Pre-preg, Molded, etc.) Joint Rings

TECHNOLOGY

Technology Description: Develop manufacturing technology for composite case membranes joined to metal joint rings on large diameter motor casings, up to 13.4 feet.

Technology Challenge: Designing joint ring structures that can demonstrate appropriate structural safety factors. Includes bending, compression, tensile strength, bearing, and shear with pinned joints, bolted joints, and clamped joints. Finding optimal fastener and joint architectures to demonstrate acceptable safety factors, and demonstrating gas sealing using composite joint surfaces are also challenges.

Technology State of the Art: This is a new technology application. Studies have been proposed for this type of joint. Composite joints have been used in other non-spacecraft applications.

Parameter, Value:	TRL
Diameter: 5 feet	2

Technology Performance Goal: Improve booster inert mass fraction by introducing tailorable joint deflection and rotation, and enabling near homogeneous material interface between the case membrane and joint region.

Parameter, Value:	TRL
Diameter: up to 13.4 feet	9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Composite case membranes integrated with composite (filament wound, pre-preg, molded, etc.) joint rings.

Capability Description: Develop manufacturing technology for improving material interface between composite case membrane joined to metal joint rings on large, up to 13.4 feet diameter, motor casing. This is one element of three booster options the Space Launch System (SLS) is trading for achieving the 130 mt capability.

Capability State of the Art: Joint ring structures are used in Graphite Epoxy Motors featuring 3.3-5 feet diameter composite cases. Current practice is to mechanically fasten or bond metal joint rings to the composite membrane.

Parameter, Value:

Diameter: 5 feet

Capability Performance Goal: Further decrease overall booster inert mass fraction, with the potential to increase payload mass by enabling tailored design stiffness optimizing joint deflection and rotation.

Parameter, Value:

Diameter: up to 13.4 feet

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

1.1 Solid Rocket Propulsion Systems
1.1.2 Case Materials

1.1.2.4 Three-Dimensional (3D) Printed (Additive Manufactured) Motor Case Membrane and Joint Technology

TECHNOLOGY

Technology Description: Motor case membranes and joints manufactured by a 3D printing (additive manufacturing) process to produce large-diameter solid rocket motor cases.

Technology Challenge: Scale-up of 3D printing technology and incorporating dual material printing to create hybrid metallic/composite structures.

Technology State of the Art: 3D printing is a fast-growing technology that is currently applied on relatively small scale applications across different industries.

Parameter, Value: Diameter: 2 feet — **TRL** 3

Technology Performance Goal: Automated manufacturing. Open trade space to designs that are currently unobtainable with classical machining and forging methods. Enable 3D printed components to be incorporated into composite structures.

Parameter, Value: Diameter: up to 13.4 feet — **TRL** 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Manufacturing and tooling for new boosters up to 13.4 feet diameter, advanced processes, and new materials.

Capability Description: Develop manufacturing technology to produce, using additive manufacturing techniques, large, up to 13.4 feet diameter, motor cases and joint rings. This is one element of three booster options Space Launch System (SLS) is trading for achieving the 130 mt capability.

Capability State of the Art: Shuttle reusable solid rocket motor (RSRM) 12.2 foot diameter metallic cases from roll forgings, etc. and Graphite Epoxy Motors 3.3-5 feet diameter composite cases.

Parameter, Value:
Diameter: 12.2 feet (forging);
Diameter: 2 feet (3D printing)

Capability Performance Goal: Additively manufactured components for 13.4 feet diameter booster.

Parameter, Value:
Diameter: up to 13.4 feet

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	2 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	2 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	2 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	2 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	2 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	2 years

1.1 Solid Rocket Propulsion Systems
1.1.2 Case Materials

1.1.2.5 Low-Cost Nano-Launch Vehicle Solid Motor Casing

TECHNOLOGY

Technology Description: Low cost solid rocket motor casing for use as propulsion for nano-launch vehicle.

Technology Challenge: Launch on demand of small satellites to optimize orbits.

Technology State of the Art: Low-cost component concepts have been designed, manufactured, and tested in ground facilities.

Parameter, Value: Cost not adequately quantified at this time. However, engine thrust and specific impulse (I_{sp}) have been adequately quantified to support vehicle stage design.

TRL: 3

Technology Performance Goal: Decrease launch costs through manufacturing of lower cost solid rocket motor components.

Parameter, Value: Cost to launch 100 lbm payload to low-Earth orbit (LEO): $1.5 M

TRL: 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Low-cost manufacturing capabilities to produce solid rocket motor casing for small nano-launcher class vehicles.

Capability Description: Ability to conduct a cost-effective dedicated launch of a small satellite to a specified orbit within a reasonable time frame (hours to days) of the desired need date.

Capability State of the Art: Current small satellite launch is dependent on rideshare with larger satellites on larger launch vehicles, and subject to the time and orbit constraints of the larger payload, often requiring waits of month to years for launch and costing approximately three times as much per pound to orbit as for a large satellite.

Parameter, Value: Cost to launch 100 lbm payload to LEO: $10 M

Capability Performance Goal: Decrease launch costs through manufacturing of lower cost solid rocket motor components.

Parameter, Value: Cost to launch 100 lbm payload to LEO: $1.5 M

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Suborbital: Science, Research & Technology (Suborbital Program)	Enhancing	--	On-going	--	3 years
Suborbital: Earth Venture Suborbital	Enhancing	--	On-going	--	3 years
Explorer Class: Explorer Missions	Enhancing	--	2023	2020	3 years

1.1 Solid Rocket Propulsion Systems
1.1.3 Nozzle Systems

1.1.3.1 Lightweight, Low-Erosion Materials

TECHNOLOGY

Technology Description: A low density, low erosion ablative material designed to reduce weight for large rocket motors.

Technology Challenge: The formulation of new, lightweight materials that feature low erosion rates and do not have ply lift or pockets.

Technology State of the Art: Material under development for Space Launch System (SLS) Advanced Booster.

Parameter, Value:

Erosion Rate: 0.018 inches/second

TRL: 2

Technology Performance Goal: Produce a low erosion ablative material with no ply lift or pocketing.

Parameter, Value:

Reduction in weight: 25%;

Reduction in erosion rate: 25%

TRL: 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Lightweight, low-erosion nozzle materials.

Capability Description: Provides reduced weight in ablative nozzle materials for solid motors.

Capability State of the Art: Nozzles have been developed for 24-inch motor subscale demonstrations.

Parameter, Value:

Erosion Rate: 18.0 mils/second

Capability Performance Goal: Need to reduce weight for nozzles and reduce erosion rate.

Parameter, Value:

Reduction in weight: 25%;

Reduction in erosion rate: 25%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

1.1 Solid Rocket Propulsion Systems
1.1.3 Nozzle Systems

1.1.3.2 Expendable Flex Bearing with Eroding Shims

TECHNOLOGY

Technology Description: Eroding shims instead of a flex boot for thermal protection for a large-scale motor.

Technology Challenge: Designing an eroding bearing that can meet the operating life and weight at reduced cost.

Technology State of the Art: Preliminary design for Space Launch System (SLS) Advanced Booster is complete and a process simulation article is being built.

Parameter, Value:

Bearing operating life: 130 seconds; Bearing weight: ~7,000 lbm

TRL 2

Technology Performance Goal: Produce eroding shims that allow flex bearing to operate throughout burn and that weigh less than current flex boot design.

Parameter, Value:

Bearing operating life: 130 seconds;

Bearing weight: ~10% reduction over the baseline design

TRL 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Expendable flex bearing with eroding shims.

Capability Description: Large-diameter, expendable eroding shim flex bearing that does not require a flexible boot seal to protect the bearing from hot gasses exhaust for use on the SLS Advanced Booster.

Capability State of the Art: Small eroding shim flex bearing in use on commercial and tactical missile systems. RSRM and SLS Initial Booster Flex bearings using a thermal flex boot seal.

Parameter, Value: Bearing operating life: 130 seconds;

Bearing weight: ~7,000 lbm

Capability Performance Goal: Simplify flex bearing design.

Parameter, Value:

Bearing operating life: 130 seconds;

Bearing weight: ~10% reduction over the baseline design

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

1.1 Solid Rocket Propulsion Systems
1.1.4 Hybrid Rocket Propulsion Systems

1.1.4.1 Low-Cost Nano-Launch Vehicle Hybrid Motor Stage

TECHNOLOGY

Technology Description: Low-cost hybrid rocket motors that can be used as propulsion for nano-launch vehicle.

Technology Challenge: Launch on demand of small satellites to optimize orbits.

Technology State of the Art: Low-cost component concepts have been designed, manufactured, and tested in ground facilities.

Parameter, Value:

Cost not adequately quantified at this time. However, motor thrust and specific impulse (I_{sp}) have been adequately quantified to support vehicle stage design.

TRL: 5

Technology Performance Goal: Decrease launch costs through manufacturing of lower cost solid rocket motor components.

Parameter, Value:

Cost to launch 100 lbm payload to LEO: $1.5 M

TRL: 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Hybrid rocket motor stage for small nano-launcher class vehicle.

Capability Description: Ability to conduct a cost-effective, dedicated launch of a small satellite to a specified orbit within a reasonable time frame (hours to days) of the desired need date.

Capability State of the Art: Current small satellite launch is dependent on rideshare with larger satellites on larger launch vehicles, and subject to the time and orbit constraints of the larger payload, often requiring waits of month to years for launch and costing approximately three times as much per pound to orbit as for a large satellite.

Parameter, Value:

Cost to launch 100 lbm payload to LEO: $10 M

Capability Performance Goal: Decrease launch costs through improved operations by utilizing a hybrid rocket motor and by manufacturing low cost hybrid rocket motor components.

Parameter, Value:

Cost to launch 100 lbm payload to LEO: $1.5 M

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Suborbital: Science, Research & Technology (Suborbital Program)	Enhancing	--	On-going	--	3 years
Suborbital: Earth Venture Suborbital	Enhancing	--	On-going	--	3 years
Explorer Class: Explorer Missions	Enhancing	--	2023	2020	3 years

1.1 Solid Rocket Propulsion Systems
1.1.5 Fundamental Solid Propulsion Technologies

1.1.5.1 Physics-Based Modeling

TECHNOLOGY

Technology Description: Models that allow for simulation of solid rocket motor and structure design. They should feature tightly coupled fluid, thermal, structural, and dynamics tools for the motor propellant, internal fluid dynamic and combustion processes; complex fluid, thermal, structural interactions; composite case; advanced liners, insulation, and nozzle materials; damage tolerance assessments; and aging and surveillance studies.

Technology Challenge: Coupling individual physics-based models and then validating the coupled capabilities.

Technology State of the Art: High-fidelity tools exist with some limited coupling. Coupled physics capabilities have not been widely validated.

Parameter, Value:	TRL
Partially validated, uncoupled physics models	4

Technology Performance Goal: Validate high-fidelity, physics-based, tightly coupled computational models to enable solid rocket motor designs that lower the cost of access to space.

Parameter, Value:	TRL
Validated, tightly coupled fluid-thermal-structural design tool	7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Space Launch System (SLS) advanced booster decision

CAPABILITY

Needed Capability: Design and analysis models for solid rocket motors. High-fidelity design tools are needed to support design of robust solid rocket motors that have significantly lower design, development, test, and evaluation (DDT&E) and production costs.

Capability Description: A computationally efficient, validated set of high fidelity, multidisciplinary design tools to support a motor design process that results in robust hardware with lower DDT&E and production costs.

Capability State of the Art: Solid motor design processes are mostly empirical. Physics-based tools do exist but are currently used as stand-alone capabilities with limited coupling capability.

Parameter, Value:

Solid motor production cost: current cost

Capability Performance Goal: Shorter, more efficient, motor design cycles that produce robust hardware with lower DDT&E and production costs.

Parameter, Value:

Solid motor production cost: 10% reduction from current cost

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	4 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	4 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	4 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	6 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	6 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	6 years

1.1 Solid Rocket Propulsion Systems
1.1.6 Integrated Solid Motor Systems

1.1.6.1 Five-Segment Advanced Solid Rocket Booster

TECHNOLOGY

Technology Description: New five-segment booster option for SLS Block 1 derived from Shuttle four-segment solid rocket booster (SRB) that provides thrust increase to meet 70 mt payload requirement.

Technology Challenge: The liner and insulation.

Technology State of the Art: Currently under development through Space Launch System (SLS) Program.

Parameter, Value:

Sea level thrust: 3,300,000 lbf

TRL 7

Technology Performance Goal: Thrust increase needed to meet 70 mt payload requirement.

Parameter, Value:

Sea level thrust: 3,300,000 lbf

TRL 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Five-segment Advanced Solid Rocket Booster.

Capability Description: New five-segment booster option for SLS Block 1 derived from Shuttle four-segment SRB that provides thrust increase to meet 70 mt payload requirement.

Capability State of the Art: Shuttle reusable solid rocket motor (RSRM) at 12.2 foot diameter produced 2,800,000 lbf thrust at sea level.

Parameter, Value:

Sea level thrust: 2,800,000 lbf

Capability Performance Goal: Thrust increase needed to meet 70 mt payload requirement.

Parameter, Value:

Sea level thrust: 3,300,000 lbf

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enabling	2022	2022	2015-2021	1 year

1.1 Solid Rocket Propulsion Systems
1.1.6 Integrated Solid Motor Systems

1.1.6.2 Advanced Large High Performance Solid Booster System Incorporating Subsystem Technologies from 1.1.1 to 1.1.3, and 1.1.7

TECHNOLOGY

Technology Description: New booster option for Space Launch System (SLS) Block 1b and 2 that provides thrust increase to meet 130 mt payload requirement.

Technology Challenge: Composite case design, manufacturing, bonding of composite case to metal joint rings, and composite damage tolerance and detection.

Technology State of the Art: Concepts have been identified and designed as part of NASA SLS Advanced Development Office (ADO) Research Announcement Study Report.

Parameter, Value:
Booster diameter: up to 13.4 feet;
Sea level thrust: 4,500,000 lbf

TRL 3

Technology Performance Goal: Increase thrust to support 130 mt payload requirement.

Parameter, Value:
Booster diameter: 13.4 feet;
Sea level thrust: 4,500,000 klbf

TRL 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Advanced, large, high-performance solid booster system.

Capability Description: New booster option for SLS Block 1b and 2 that provides thrust increase to meet 130 mt payload requirement. This is one element of three booster options SLS is trading for achieving the 130 mt capability.

Capability State of the Art: Shuttle reusable solid rocket motor (RSRM) producing 2,800,000 lbf thrust at sea level and SLS initial five-segment booster under development, producing 3,300,000 lbf at sea level

Parameter, Value:
Booster diameter: 12.2 feet;
Sea level thrust: 2,800,000 lbf

Capability Performance Goal: Increased thrust to support 130 mt payload requirement.

Parameter, Value:
Booster diameter: up to 13.4 feet;
Sea level thrust: 4,500,000 lbf

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

1.1 Solid Rocket Propulsion Systems
1.1.6 Integrated Solid Motor Systems

1.1.6.3 Low-Cost Nano-Launch Vehicle Solid Motor Stage

TECHNOLOGY

Technology Description: Low-cost solid rocket motor for use as propulsion for nano-launch vehicle.

Technology Challenge: Launch on demand of small satellites to optimize orbits.

Technology State of the Art: Low-cost component concepts have been designed, manufactured, and tested in ground facilities.

Parameter, Value: Cost not adequately quantified at this time. However, engine thrust and specific impulse (I_{sp}) have been adequately quantified to support vehicle stage design.

TRL: 4

Technology Performance Goal: Decrease launch costs through manufacturing of lower cost solid rocket motor components.

Parameter, Value: Cost to launch 100 lbm payload to low-Earth orbit (LEO): $1.5 M

TRL: 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Solid rocket motor stage for small nano-launcher class vehicle.

Capability Description: Ability to conduct a cost-effective dedicated launch of a small satellite to a specified orbit within a reasonable time frame (hours to days) of the desired need date.

Capability State of the Art: Current small satellite launch is dependent on rideshare with larger satellites on larger launch vehicles, and subject to the time and orbit constraints of the larger payload, often requiring waits of month to years for launch and costing approximately three times as much per pound to orbit as for a large satellite.

Parameter, Value: Cost to launch 100 lbm payload to LEO: $10 M

Capability Performance Goal: Decrease launch costs through manufacturing of lower cost solid rocket motor components.

Parameter, Value: Cost to launch 100 lbm payload to LEO: $1.5 M

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Suborbital: Science, Research & Technology (Suborbital Program)	Enhancing	--	On-going	--	3 years
Suborbital: Earth Venture Suborbital	Enhancing	--	On-going	--	3 years
Explorer Class: Explorer Missions	Enhancing	--	2023	2020	3 years

1.1 Solid Rocket Propulsion Systems
1.1.7 Liner and Insulaton

1.1.7.1 Polybenzimidazole Acrylonitrile Butadiene Rubber (PBI NBR) Based Asbestos-Free Liner and Insulation

TECHNOLOGY

Technology Description: Reformulation of insulation using an alternative to asbestos.

Technology Challenge: Currently there are process issues, creating significant rework or scraping of large cast motor segments.

Technology State of the Art: This technology is under development in the Space Launch System (SLS) Booster project. However, certain issues remain that may require further technology assessment.

Parameter, Value:

Current case material temperature limits insulation voids: 10 per motor segment;

Propellant/liner/insulation voids: 1 per motor segment

TRL 7

Technology Performance Goal: Achieve the same levels of internal temperature as existing solid rocket motors, but whithout the use of asbestos.

Parameter, Value:

Insulation voids: 0 per motor segment;

Propellant/liner/insulation voids: 0 per motor segment

TRL 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Asbestos-free liner and insulation.

Capability Description: Solid rocket motor casings using this type of insulation will maintain internal temperature below thermal limits without use of asbestos as an insulating material. Previous systems operated with a waver; new systems cannot have a waver, thus new asbestos-free options must be developed.

Capability State of the Art: Shuttle reusable solid rocket motor (RSRM) was asbestos based. The Shuttle's RSRM required a waver to operate the last few years.

Parameter, Value:

Current case material temperature limits

Capability Performance Goal: Achieve the same levels of internal temperature without the use of asbestos.

Parameter, Value:

Not Applicable

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Extending Reach Beyond LEO: DRM 5 Asteroid Redirect – Robotic Spacecraft	Enabling	2015	2018	2015	1 year
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enabling	2022	2022	2015-2021	1 year
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

1.1 Solid Rocket Propulsion Systems
1.1.7 Liner and Insulaton

1.1.7.2 Insulating/Ablative Sprayable Liner

TECHNOLOGY

Technology Description: This is a liner capable of insulative properties similar to fiber-filled nitrile butadiene rubber (NBR) and ethylene propylene diene monomer (EPDM) insulations. Includes significant weight reduction and elimination of process issues addressed today.

Technology Challenge: Producing an acceptable sprayable liner is a technical challenge.

Technology State of the Art: This technology is under development in Space Launch System (SLS) Booster project. Current issues remain that may require further technology development.

Parameter, Value:	TRL
Current case material weight	5

Technology Performance Goal: Reduce insulation weight by reducing insulation thickness.

Parameter, Value:	TRL
Motor gross weight (inert): 25% reduction in insulation weight	9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: A sprayable liner.

Capability Description: The sprayable liner can maintain the solid rocket booster motor case internal temperature below thermal limits without use of asbestos as an insulating material. Previous systems operated with a waver; new systems cannot have a waver, thus new asbestos-free options must be developed.

Capability State of the Art: Reusable Solid Rocket Motor (RSRM) Carbon Black Based Liner. The Shuttle's RSRM required a waver to operate the last few years.

Parameter, Value:
Current case material weight

Capability Performance Goal: Need to achieve same levels of internal temperature without use of asbestos.

Parameter, Value:
Motor gross weight (inert): 25% reduction in insulation weight

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Extending Reach Beyond LEO: DRM 5 Asteroid Redirect – Robotic Spacecraft	Enabling	2015	2018	2015	1 year
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enabling	2022	2022	2015-2021	1 year
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

1.2 Liquid Rocket Propulsion Systems
1.2.1 LH_2 / LOX Based

1.2.1.1 J-2X Upper Stage Engine

TECHNOLOGY

Technology Description: The J-2X is a throttleable, liquid-fueled cryogenic rocket engine designed for upper stage use.

Technology Challenge: Include materials and manufacturing techniques for the nozzle extension.

Technology State of the Art: Engine development halted before completion due to lack of mission need.

Parameter, Value:

Thrust Level (vacuum): 294,000 lbf;

Vacuum specific impulse (I_{sp}): 448 seconds

TRL: 7

Technology Performance Goal: Need increased thrust and I_{sp} to support original Ares I, Ares V, and Space Launch System (SLS) configurations.

Parameter, Value:

Thrust Level (vacuum), 294,000 lbf;

Vacuum I_{sp}: 448 seconds

TRL: 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: The J-2X is a throttleable, liquid-fueled upper stage engine.

Capability Description: The J-2X can provide 294,000 pounds of thrust, and in-space restart while operating at nominal to 80% of nominal throttle setting.

Capability State of the Art: No capability exists in this thrust class today.

Parameter, Value:

Not Applicable

Capability Performance Goal: Needed increased thrust and I_{sp} to support original Ares I, Ares V, and SLS configurations.

Parameter, Value:

Thrust Level (vacuum): 294,000 lbf;

Vacuum I_{sp}: 448 seconds

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years

1.2 Liquid Rocket Propulsion Systems
1.2.1 LH_2 / LOX Based

1.2.1.2 Space Shuttle Main Engine (RS-25D) Modified

TECHNOLOGY

Technology Description: Adaptation of existing RS-25D engines to the Space Launch System (SLS) Core Stage for Block 1 to provide needed core stage thrust.

Technology Challenge: The Space Shuttle Main Engine was originally designed to operate with inlet pressures that are lower than will be developed by the taller SLS vehicle.

Technology State of the Art: Design analysis that assesses engine hardware capability under higher inlet pressures.

Parameter, Value:	TRL
Operation at inlet pressures produced by height of SLS Core Stage.	7

Technology Performance Goal: Operation at inlet pressures produced by height of SLS Core Stage.

Parameter, Value:	TRL
Operation at inlet pressures produced by height of SLS Core Stage.	9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: High-thrust, high-inlet-pressure engine.

Capability Description: Provides engines that can operate with higher inlet pressures of taller SLS vehicle and provides thrust for SLS Block 1 to lift 70 mt of cargo or crew to low-Earth orbit (LEO).

Capability State of the Art: RS-25D last used on Shuttle. Currently not in active use.

Parameter, Value:
Operation at inlet pressures produced by height of external tank.

Capability Performance Goal: Operation at inlet pressures produced by height of SLS Core Stage.

Parameter, Value:
Operation at inlet pressures produced by height of SLS Core Stage.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed to DRO	Enabling	2022	2022	2015-2021	1 year

1.2 Liquid Rocket Propulsion Systems
1.2.1 LH_2 / LOX Based

1.2.1.3 RS-25 Expendable Engine

TECHNOLOGY

Technology Description: Derivative RS-25 to accommodate production capabilities for reduced cost and make engine expendable without compromising on current RS-25D performance.

Technology Challenge: Manufacturing processes and materials, and integrated system interactions.

Technology State of the Art: Conceptual design trade studies have been performed to identify options to achieve goals.

Parameter, Value:

Needed production rate and cost to support planned Space Launch System (SLS) mission needs.

TRL: 3

Technology Performance Goal: Produce a low-cost, expendable version of the Space Shuttle Main Engine without losing performance.

Parameter, Value:

Production cost, $M: will be defined by design;

Production rate, number per year: will be defined by design

TRL: 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: RS-25E Expendable Engine.

Capability Description: Provides expendable engine without compromising on current RS-25D performance. Provides thrust for SLS Block 1 to lift 105 mt and 130 mt of cargo or crew to low-Earth orbit (LEO).

Capability State of the Art: RS-25D last used on Shuttle. Currently not in active use.

Parameter, Value:

Cost, $M: Not Applicable;

Production Rate, number per year: 0

Capability Performance Goal: Needed production rate and cost to support planned SLS mission needs.

Parameter, Value:

Cost, $M: will be defined by design;

Production Rate, number per year: will be defined by design

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

1.2 Liquid Rocket Propulsion Systems
1.2.1 LH_2 / LOX Based

1.2.1.4 Common Upper Stage / In-Space Stage

TECHNOLOGY

Technology Description: Upper stage engine that can function as in-space engine for transfer stages as well as an Earth-to-orbit stage.

Technology Challenge: Engine performance level and manufacturing processes and materials.

Technology State of the Art: Technology demonstration hardware has been fabricated but not yet tested.

Parameter, Value:
Thrust Level (vacuum): 60,000 lbf;
Vacuum specific impulse (I_{sp}): ~465 seconds

TRL 3

Technology Performance Goal: Enable the evolved Space Lauch System (SLS).

Parameter, Value:
Thrust Level (vacuum): 60,000 lbf;
Vacuum I_{sp}: ~465 seconds

TRL 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Common upper stages and in-space transfer stage.

Capability Description: The new upper stage engine will be designed to provide 60,000 lbf of thrust with an I_{sp} of about 465 seconds to enable the evolved SLS to deliver 105 mt and 130 mt.

Capability State of the Art: The RL10B-2.

Parameter, Value:
Thrust Level (vacuum): 24,000 lbf;
Vacuum I_{sp}: 462 seconds

Capability Performance Goal: Enable the evolved SLS.

Parameter, Value:
Thrust Level (vacuum): 60,000 lbf;
Vacuum I_{sp}: ~465 seconds

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

1.2 Liquid Rocket Propulsion Systems
1.2.2 RP / LOX Based

1.2.2.1 Oxygen-Rich Staged Combustion (ORSC) Cycle Engine

TECHNOLOGY

Technology Description: Large Oxygen-Rich Staged Combustion (ORSC) Cycle rocket propellant (RP)/liquid oxygen (LOX) engine for use as booster propulsion.

Technology Challenge: ORSC manufacturing processes and materials properties, advanced tooling and machines, combustion instability, pre-burner, thrust chamber assembly, and turbopump design.

Technology State of the Art: ORSC engine design concepts have been developed through Preliminary Design Review level and some key components have been manufactured and tested.

Parameter, Value:

No performance in testing/development

TRL: 3

Technology Performance Goal: Develop an engine to enable delivery of 130 mt to low-Earth orbit (LEO).

Parameter, Value:

Thrust Level (vacuum): 1.2 Mlbf;

Specific Impulse (I_{sp}): ~338 seconds

TRL: 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Advanced liquid booster engine.

Capability Description: New full scale ORSC (RD-180 class) 1.2 Mlbf, I_{sp} ~338 seconds for advanced liquid booster for the Space Launch System (SLS) Block 2 to enable delivery of 130 mt to LEO. This is one element of three booster options SLS is trading for achieving the 130 mt capability.

Capability State of the Art: The Russian RD-180.

Parameter, Value:

Thrust Level (vacuum): 933,000 lbf;

Vacuum I_{sp}: 338 seconds

Capability Performance Goal: Develop an engine to enable delivery of 130 mt to LEO.

Parameter, Value:

Thrust Level (vacuum): 1.2 Mlbf;

I_{sp}: ~338 seconds

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

1.2 Liquid Rocket Propulsion Systems
1.2.2 RP / LOX Based

1.2.2.2 Large F-1 Class Gas Generator (GG) Cycle Engine

TECHNOLOGY

Technology Description: Large gas generator (GG) cycle rocket propellant (RP)/liquid oxygen (LOX) engine for use as booster propulsion.

Technology Challenge: Manufacturing processes and materials, combustion instability, mature forging, casting capability, and reduced cost with advanced manufacturing processes and machines.

Technology State of the Art: Assessment of restarting of F-1 production and development planning has taken place. Sample components have been manufactured using modern capabilities.

Parameter, Value:

No performance in testing/development

TRL: 3

Technology Performance Goal: Develop an engine to enable delivery of 130 mt to low-Earth orbit (LEO).

Parameter, Value:

Thrust Level (vacuum): 2,000,000 lbf;

Specific impulse (I_{sp}): ~303 seconds

TRL: 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Large GG cycle engine.

Capability Description: New 2 Mlbf GG cycle oxygen/kerosene, I_{sp} ~303 seconds for advanced liquid booster for the Space Launch System (SLS) Block 2 to enable delivery of 130 mt to LEO. This is one element of 3 booster options SLS is trading for achieving the 130 mt capability.

Capability State of the Art: Merlin 1D Engine.

Parameter, Value:

Vacuum thrust: 155,000 lbf;

Vacuum I_{sp}: 310 seconds

Capability Performance Goal: Develop an engine to enable delivery of 130 mt to low-Earth orbit (LEO).

Parameter, Value:

Thrust Level (vacuum): 2,000,000 lbf;

I_{sp}: ~303 seconds

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

1.2 Liquid Rocket Propulsion Systems
1.2.2 RP / LOX Based

1.2.2.3 Low-Cost Nano-Launch Vehicle Stage Engine (Rocket Propellant)

TECHNOLOGY

Technology Description: Low cost pressure fed cycler rocket propellant (RP)-1/liquid oxygen (LOX) engines for use as propulsion for nano-launch vehicle.

Technology Challenge: Launch on demand of small satellites to optimize orbits.

Technology State of the Art: Low-cost component concepts have been designed, manufactured, and tested in ground facilities.

Parameter, Value:
Cost not adequately quantified at this time. However, engine thrust and I_{sp} have been adequately quantified to support vehicle stage design.

TRL: 4

Technology Performance Goal: Decrease launch costs through manufacturing of lower cost stage propulsion components

Parameter, Value:
Cost to launch 100 lbm payload to low-Earth orbit (LEO): $1.5 M

TRL: 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Engines for small nano-launcher class vehicle.

Capability Description: Ability to conduct a cost-effective dedicated launch of a small satellite to a specified orbit within a reasonable time frame (hours to days) of the desired need date.

Capability State of the Art: Current small satellite launch is dependent on rideshare with larger satellites on larger launch vehicles, and subject to the time and orbit constraints of the larger payload, often requiring waits of month to years for launch and costing approximately three times as much per pound to orbit as for a large satellite.

Parameter, Value:
Cost to launch 100 lbm payload to LEO: $10 M

Capability Performance Goal: Decrease launch costs through manufacturing of lower cost stage propulsion components.

Parameter, Value:
Cost to launch 100 lbm payload to LEO: $1.5 M

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Suborbital: Science, Research & Technology (Suborbital Program)	Enhancing	--	On-going	--	3 years
Suborbital: Earth Venture Suborbital	Enhancing	--	On-going	--	3 years
Explorer Class: Explorer Missions	Enhancing	--	2023	2020	3 years

1.2 Liquid Rocket Propulsion Systems
1.2.3 CH_4 / LOX Based

1.2.3.1 Low-Cost Nano-Launch Vehicle Stage Engine (Methane)

TECHNOLOGY

Technology Description: Low-cost pressure-fed cycle liquid oxygen (LOX)/methane (CH_4) engines for use as propulsion for nano-launcher class vehicle.

Technology Challenge: Launch on demand of small satellites to optimize orbits.

Technology State of the Art: Low-cost component concepts have been designed, manufactured, and tested in ground facilities.

Parameter, Value:

Cost not adequately quantified at this time. However, engine thrust and I_{sp} have been adequately quantified to support vehicle stage design.

TRL: 4

Technology Performance Goal: Decrease launch costs through manufacturing of lower cost stage propulsion components.

Parameter, Value:

Cost to launch 100 lbm payload to low-Earth orbit (LEO): $1.5 M

TRL: 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Engines for small nano-launcher class vehicle.

Capability Description: Ability to conduct a cost-effective dedicated launch of a small satellite to a specified orbit within a reasonable time frame (hours to days) of the desired need date.

Capability State of the Art: Current small satellite launch is dependent on rideshare with larger satellites on larger launch vehicles, and subject to the time and orbit constraints of the larger payload, often requiring waits of month to years for launch and costing approximately three times as much per pound to orbit as for a large satellite.

Parameter, Value:

Cost to launch 100 lbm payload to LEO: $10 M

Capability Performance Goal: Decrease launch costs through manufacturing of lower cost stage propulsion components.

Parameter, Value:

Cost to launch 100 lbm payload to LEO: $1.5 M

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Suborbital: Science, Research & Technology (Suborbital Program)	Enhancing	--	On-going	--	3 years
Suborbital: Earth Venture Suborbital	Enhancing	--	On-going	--	3 years
Explorer Class: Explorer Missions	Enhancing	--	2023	2020	3 years

1.2 Liquid Rocket Propulsion Systems
1.2.6 Fundamental Liquid Propulsion Technologies

1.2.6.1 Advanced Design and Analysis Tools

TECHNOLOGY

Technology Description: These fully integrated models involve tightly coupled fluid, thermal, structural/structural dynamics that accurately simulate liquid rocket engine performance, stability, fluid, thermal, and structural characteristics.

Technology Challenge: Challenges include coupling the individual physics-based models, obtaining sufficient test data to anchor developed models and codes, validating the coupled capabilities, balancing between model fidelity and efficiency, and integration of models into existing design methodologies.

Technology State of the Art: High-fidelity tools exist with some limited coupling. Coupled physics capabilities are largely unvalidated.

Parameter, Value:	TRL
Partially validated, uncoupled physics models.	4

Technology Performance Goal: Produce validated high-fidelity, physics-based, tightly coupled computationally models to enable liquid rocket engine designs that lower the cost of access to space.

Parameter, Value:	TRL
Adequately validated, tightly-coupled fluid-thermal-structural design tool.	7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: These models are high-fidelity design tools to support design of robust liquid rocket engines that have significantly lower design, development, test, and evaluation (DDT&E) and production costs, as well as reduced design cycle times.

Capability Description: These models represent a computationally efficient, validated set of high-fidelity, multidisciplinary design tools to support a motor design process that results in robust hardware with lower DDT&E and production costs and shorter hardware delivery schedules for new liquid propulsion systems identified in 1.2.1 and 1.2.2.

Capability State of the Art: Design process is mostly empirical. Physics-based tools do exist but are currently used as the stand-alone capabilities with limited coupling capability.

Parameter, Value:

Current design cycle time and costs.

Capability Performance Goal: Reduced time and cost of design cycles.

Parameter, Value:

Reduction of design cycle time and costs by 25-50% each

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	4 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	4 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	4 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	6 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	6 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	6 years

1.2 Liquid Rocket Propulsion Systems
1.2.6 Fundamental Liquid Propulsion Technologies

1.2.6.2 Advanced Engine Component Manufacturing

TECHNOLOGY

Technology Description: Production of advanced, low-cost cryogenic and rocket propulsion components through advanced materials and improved production methods.

Technology Challenge: Challenges include maintaining low mass, design simplification for production, development of acceptable process controls, and demonstrations and further development of materials properties.

Technology State of the Art: Various manufacturing demonstrations and limited functional demonstrations (hot fires, etc.) have been conducted.

Parameter, Value:	**TRL**
Current production costs	4

Technology Performance Goal: Lower costs for liquid-fueled rocket engines.

Parameter, Value:	**TRL**
Reduction in production costs: 50-75%	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Low cost propulsion system components.

Capability Description: Evolutionary development of robust, low-cost engine components for expendable and reusable launch vehicles using materials advances and improved production methods would greatly reduce production costs and improve reliability for reusable applications.

Capability State of the Art: Cryogenic and rocket propulsion components are currently produced using conventional methods.

Parameter, Value:
Current production costs

Capability Performance Goal: Lower cost depending on component application.

Parameter, Value:
Reduction in production costs: 50-75%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Extending Reach Beyond LEO: DRM 5 Asteroid Redirect – Robotic Spacecraft	Enhancing	2015	2018	2015	1 year
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	1 year
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	5 years

1.4 Ancillary Propulsion Systems
1.4.1 Auxillary Control Systems

1.4.1.1 Low-Cost, High Thrust-to-Weight Ratio 100 lbf Class Reaction Control Systems (RCS)

TECHNOLOGY

Technology Description: Develop thrusters with moderate-to-long life capability, comparable to or improved upon state of the art, and lower system mass.

Technology Challenge: Life extension (throughput and thermal cycles). Current high thrust-to-weight thrusters in missile applications have lives measured in minutes.

Technology State of the Art: This technology has been demonsrated in exoatmospheric missiles and in ground altitude chambers.

Parameter, Value:

Lower mass and cost with equivalent or improved specific impulse (I_{sp}) and I_{sp} density

TRL 5

Technology Performance Goal: Continue development of a high thrust-to-weight thruster for spacecraft and lander missions. The Technology Readiness Level (TRL) is dependent on development takeover requirements.

Parameter, Value:

System mass: 1 lbm;

System cost: $100,000

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: High thrust-to-weight RCS.

Capability Description: Current RCS monopropellant or bi-propellant systems are very costly. New materials and production techniques could reduce thruster cost, as well as reduce the weight of the support systems.

Capability State of the Art: 100 lbf class monomethylhydrazine/dinitrogen tetroxide (N_2O_4) bi-propellant reaction control systems.

Parameter, Value:

System mass: 8 lbm;

System cost: $800,000

Capability Performance Goal: Develop an RCS with constant or better I_{sp} with reduced propellant system mass and reduced cost.

Parameter, Value:

System mass: 1 lbm;

System cost: $100,000

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Extending Reach Beyond LEO: DRM 5 Asteroid Redirect – Robotic Spacecraft	Enhancing	2015	2018	2015	1 year
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	1 year
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	3 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	3 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	3 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	3 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	3 years

1.4 Ancillary Propulsion Systems
1.4.1 Auxillary Control Systems

1.4.1.2 Nontoxic Reaction Control Propellants

TECHNOLOGY

Technology Description: Nontoxic reaction control system (RCS) propellants can reduce ground infrastructure cost and complexity, improve ground safety and operational timelines, and potentially reduce flight vehicle system production costs and improve performance.

Technology Challenge: Propellant material compatibility and small, lightweight cryogenic lines and valves.

Technology State of the Art: Various previous technology efforts have been conducted, many of which have ended in ground hot-fire demonstrations.

Parameter, Value:	**TRL**
Nontoxic operation with acceptable performance (specific impulse (I_{sp}) and propellant density)	4

Technology Performance Goal: Develop promising propellant combinations to "flight like prototype" and perform demonstrations in a required relevant environment.

Parameter, Value:	**TRL**
Nontoxic operation while meeting performance of state of the art (I_{sp} and propellant density)	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Nontoxic reaction control system.

Capability Description: Provide reaction control propulsion capability using nontoxic propellant combination while maintaining or surpassing performance (I_{sp} and total propellant density).

Capability State of the Art: Hydrazine mono-propellant, or Hydrazine/dinitrogen tetroxide (N_2O_4) bi-propellant reaction control systems.

Parameter, Value:

Toxicity

Capability Performance Goal: Produce a non-toxic propellant combination with equal or improved overall performance (I_{sp} and overall propellant density) to existing RCS.

Parameter, Value:

Nontoxic operation, while meeting performance of state of the art (I_{sp} and propellant density)

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Extending Reach Beyond LEO: DRM 5 Asteroid Redirect – Robotic Spacecraft	Enhancing	2015	2018	2015	1 year
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	1 year
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	3 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	3 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	3 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	3 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	3 years

1.4 Ancillary Propulsion Systems
1.4.1 Auxillary Control Systems

1.4.1.3 Low Cost Reaction Control System (RCS) for Small Launch (Microsat Launch Vehicle or Nano-Launcher)

TECHNOLOGY

Technology Description: This technology is designed to provide reaction control propulsion capability using commercial-off-the-shelf (COTS) or additive manufacturing components that enhance affordability and meet reduced performance and reliability requirements.

Technology Challenge: Launch on demand of small satellites to optimize orbits.

Technology State of the Art	TRL	Technology Performance Goal	TRL
Technology State of the Art: A cold gas prototype system was flown in 2013 but not successfully demonstrated.		**Technology Performance Goal:** Meet a cost target of less than $50,000 per system and still meet performance and reliability requirements.	
Parameter, Value: Cost value has not been established for a small satellite launcher as this is a new launch capability.	3	**Parameter, Value:** Cost to launch 100 lbm payload to low-Earth orbit (LEO): $1.5 M	9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Affordable RCS is designed to meet reduced performance and reliability requirements.

Capability Description: There is a market of payload class which have lower orbital injection accuracy requirements than typical NASA missions. This allows reduction in performance and reliability requirements and allows enhancement of affordability through use of COTS or additive manufacturing processes.

Capability State of the Art: Cold gas, small solid, or storable liquid monopropellant (hydrogen peroxide (H_2O_2)).

Parameter, Value:
Enhance affordability and meet reduced performance and reliability requirements.

Capability Performance Goal: Meet a cost target of less than $50,000 per system and still meet performance and reliability requirements.

Parameter, Value:
Cost to launch 100 lbm payload to LEO: $1.5 M

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Suborbital: Science, Research & Technology (Suborbital Program)	Enhancing	--	On-going	--	3 years
Suborbital: Earth Venture Suborbital	Enhancing	--	On-going	--	3 years
Explorer Class: Explorer Missions	Enhancing	--	2023	2020	3 years

1.4 Ancillary Propulsion Systems
1.4.2 Main Propulsion Systems (Excluding Engines)

1.4.2.1 Advanced, Low-Cost Cryogenic and Rocket Propellant (RP) Components

TECHNOLOGY

Technology Description: Production of advanced, low-cost cryogenic and RP components through advanced materials and improved production methods.

Technology Challenge: Challenges with these technologies are maintaining low mass, simplification of design for production, and development of acceptable process controls. Demonstrations and further development of materials properties is required.

Technology State of the Art: Various manufacturing demonstrations and limited functional demonstrations (hot fires, etc.) have been conducted.

Parameter, Value:	**TRL**
Reduction in production cost	4

Technology Performance Goal: Lower cost depending on component application. The Technology Readiness Level (TRL) is dependent on development takeover requirements.

Parameter, Value:	**TRL**
Reduction in production costs: 50-75%	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Low cost propulsion system components.

Capability Description: Evolutionary development of robust, low-cost fill and drain, recirculation, engine isolation valves, ducts, recirculation pumps, and cryogenic helium regulators for expendable and reusable launch vehicles using materials advances and improved production methods, could greatly reduce production costs and improve reliability for reusable applications.

Capability State of the Art: Cryogenic and RP components are currently produced using conventional methods.

Parameter, Value:
Current production costs

Capability Performance Goal: Lower cost depending on component application.

Parameter, Value:
Reduction in production costs: 50-75%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Extending Reach Beyond LEO: DRM 5 Asteroid Redirect – Robotic Spacecraft	Enhancing	2015	2018	2015	1 year
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	1 year
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	5 years

1.4 Ancillary Propulsion Systems
1.4.3 Launch Abort Systems

1.4.3.1 Vectorable High-Thrust Abort Motor

TECHNOLOGY

Technology Description: This technology incorporates low-cost, highly maneuverable thrust vector control (TVC) systems used in large solid rocket motors.

Technology Challenge: Developing a large TVC system that can respond quickly represents a challenge.

Technology State of the Art: Current large TVC systems are slow to respond. Fast reaction time systems require another separate motor.

Parameter, Value: Large size high slew rate TVC are not readily available.

TRL: 3

Technology Performance Goal: Demonstrate TVC with high slew rates under high thrust conditions, vehicle control over flight dynamics. The Technology Readiness Level (TRL) is dependent on development takeover requirements.

Parameter, Value: Vehicle control over flight dynamics.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Low-cost, highly maneuverable thrust vector controlled motor.

Capability Description: High-thrust abort motor designs with vectorable thrust enable improved launch abort vehicles control through all flight regimes. High-thrust TVC also requires high slew rate, high slew angle, high thrust (50,000-150,000 lbf) solid propellant motors and associated systems.

Capability State of the Art: Vector control is applied via separate motor system or too slow for rapid response.

Parameter, Value: Current two-motor approach

Capability Performance Goal: Produce a low-cost single motor with a high reaction time.

Parameter, Value: Elimination of separate control motors

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Extending Reach Beyond LEO: DRM 5 Asteroid Redirect – Robotic Spacecraft	Enhancing	2015	2018	2015	1 year
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	1 year
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	5 years

1.4 Ancillary Propulsion Systems
1.4.3 Launch Abort Systems

1.4.3.2 Integrated Liquid Propulsion Bi-Propellant Ascent Abort System

TECHNOLOGY

Technology Description: Integrated propulsion systems that employ liquid propellants capable of providing both the high thrust required for vehicle abort and low thrust required for on-orbit maneuvering and attitude control.

Technology Challenge: Key challenges include meeting a broad requirements range within a single system and rapid thrust initiation requirements.

Technology State of the Art: High-thrust engines have been ground tested in vacuum chambers and at sea-level. Dual chambers are to account for changing ambient pressures during ascent.

Parameter, Value:	TRL
Specific impulse (I_{sp}): current; Start time: current; Thrust-to-weight: current	3

Technology Performance Goal: Revive existing liquid abort engine efforts, add throttling capability, increase efficiency, and increase thrust-to-weight ratio. The Technology Readiness Level (TRL) is dependent on development takeover requirements.

Parameter, Value:	TRL
I_{sp}: 315 seconds (min); Start time: 500 ms (max); Thrust-to-weight: 50+	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Liquid propellant integrated abort system.

Capability Description: Provide high-thrust, rapid-start liquid propulsion system for ascent abort (from T-0 through abort-once-around).

Capability State of the Art: Current solid motors have high-acceleration, single burn with a pre-specified thrust profile, 270 sec I_{sp}. Abort propellant ejected once abort-once-around is achieved.

Parameter, Value:

I_{sp}: 270 seconds;
Start time: current;
Thrust-to-weight: current

Capability Performance Goal: 3:1 throttling, integrated with an in-space propulsion system (propellant available for use once orbit is achieved), 315 sec I_{sp} (min).

Parameter, Value:

Fast-response, high-pressure, mid-thrust; (3,000-5,000 lbf or higher) propulsion systems, with variable thrust/second

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Extending Reach Beyond LEO: DRM 5 Asteroid Redirect – Robotic Spacecraft	Enhancing	2015	2018	2015	1 year
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	1 year
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	5 years

1.4 Ancillary Propulsion Systems
1.4.3 Launch Abort Systems

1.4.3.3 Solid Propellant Thrust Termination/Abort System

TECHNOLOGY

Technology Description: This technology provides low-cost thrust termination and safe ascent abort system for launch vehicles.

Technology Challenge: Innovative, low cost solutions to existing need.

Technology State of the Art: Linear shaped charges, high cost antennas, and receiver avionics.

Parameter, Value:	TRL
Cost: abort system cost currently exceeds cost of main propulsion stage	3

Technology Performance Goal: Low cost integrated system meeting existing requirements.

Parameter, Value:	TRL
Cost: abort system cost currently exceeds cost of main propulsion stage	3

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: This is a low-cost thrust termination and safe ascent abort system for launch vehicles.

Capability Description: This technology represents an affordable system capable of providing the thrust termination required for safe abort and de-orbit with a reliable high communication link in an integrated package.

Capability State of the Art: Solid motors, linear shaped charges, high cost antennas, and receiver avionics collectively represent the state of the art.

Parameter, Value:

Cost: abort system cost currently exceeds cost of main propulsion stage

Capability Performance Goal: 50% reduction in cost of these systems.

Parameter, Value:

Cost: abort system cost currently exceeds cost of main propulsion stage

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Extending Reach Beyond LEO: DRM 5 Asteroid Redirect – Robotic Spacecraft	Enhancing	2015	2018	2015	1 year
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	1 year
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	5 years

1.4 Ancillary Propulsion Systems
1.4.4 Thrust Vector Control Systems

1.4.4.1 Nontoxic Propellant-Driven, Turbine-Based Auxiliary Power Units

TECHNOLOGY

Technology Description: Replacement technology for hydrazine-driven hydraulic power units using either nontoxic propellant or a blow-down type system.

Technology Challenge: Integrated vehicle impacts.

Technology State of the Art: Concept development has been explored with limited subsystem demonstrations; however, integrated system demonstrations and further development required.

Parameter, Value:	**TRL**
Technology is conceptually capable of performance goals. However, integrated system demonstrations and further development is required.	4

Technology Performance Goal: Develop promising propellants and hardware combinations to a “flight like prototype” level and perform demonstrations in required relevant environments. The Technology Readiness Level (TRL) is dependent on takeover requirements.

Parameter, Value:	**TRL**
Nontoxic while meeting performance of the state of the art	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: This is a nontoxic turbine power unit for use in hydraulic pressurization.

Capability Description: This technology provides turbine power capability with nontoxic propellant while maintaining or surpassing performance of currently available systems.

Capability State of the Art: Hydrazine-driven, turbine-based auxiliary power units.

Parameter, Value:

Toxicity

Capability Performance Goal: Produce a nontoxic propellant driven turbine power unit with equal or improved overall performance.

Parameter, Value:

Nontoxic while meeting performance of the state of the art

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Extending Reach Beyond LEO: DRM 5 Asteroid Redirect – Robotic Spacecraft	Enhancing	2015	2018	2015	1 year
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	1 year
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	3 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	3 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	3 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	3 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	3 years

1.4 Ancillary Propulsion Systems
1.4.4 Thrust Vector Control Systems

1.4.4.2 Advanced Actuator and Controller Development (Electro-Hydraulic Actuator (EHA), Electromechanical Actuator (EMA), Integrated Actuator Package (IAP))

TECHNOLOGY

Technology Description: This is a low-cost actuator system for an integrated thrust vector control (TVC) system.

Technology Challenge: Fault tolerance and power draw represent challenges with this technology.

Technology State of the Art: Concept development has been explored, with limited subsystem demonstrations.

Parameter, Value: Technology is conceptually capable of performance goals. However, integrated system demonstrations and further development is required.

TRL 3

Technology Performance Goal: Demonstrate reprogrammable controllers using multiple actuators that have met redundancy requirements.

Parameter, Value: Lower cost while meeting performance requirements.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: This low-cost actuator can be used in an integrated TVC system.

Capability Description: EHA, EMA, and IAPs can be used on a wide range of launch vehicles, especially those that are reusable, for similar, lower cost integrated TVC systems.

Capability State of the Art: Hydraulic actuators with matched controllers designed for a specific purpose represent SOA (small EMAs for expendable launch vehicle upper stages).

Parameter, Value: Affordability and reliability.

Capability Performance Goal: Produce reprogrammable controllers with redundancy managed actuators.

Parameter, Value: Lower cost while meeting performance and redundancy requirements.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Extending Reach Beyond LEO: DRM 5 Asteroid Redirect – Robotic Spacecraft	Enhancing	2015	2018	2015	1 year
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	1 year
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	3 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	3 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	3 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	3 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	3 years

1.4 Ancillary Propulsion Systems
1.4.4 Thrust Vector Control Systems

1.4.4.3 Corona-Proof, Rapid Charge/Discharge High Power Battery and Power Distribution Systems

TECHNOLOGY

Technology Description: Limiting factor for electromechanical actuator (EMA) usage on larger systems is the power management system. Seek to utilize developments in battery and regen systems to enable power management for new actuator systems.

Technology Challenge: Lightweight shielding, robust battery, and circuit reliability and survivability.

Technology State of the Art: Battery and regen systems for small upper stage actuation applications currently exist.

Parameter, Value: Technology is conceptually capable of performance goals. However, integrated system demonstrations and further development is required.

TRL 3

Technology Performance Goal: Demonstrate performance of high power electrical system for actuation.

Parameter, Value: Demonstrate performance of high power electrical system for actuation that meets current requirements for performance and corona.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: A corona-proof, high power, rapid charge/discharge battery and power distribution system.

Capability Description: Advanced actuators will require greater electrical power from a high-voltage, rapid charge/discharge battery and distribution system. This system must be developed to avoid corona effects during ascent.

Capability State of the Art: Hydrazine or hydrogen power sources are currently used for high power actuation systems.

Parameter, Value: Performance of high-power system in rapid charge/discharge environment.

Capability Performance Goal: Produce a high-power battery and regenerative circuit.

Parameter, Value: High-power circuit that meets corona requirements.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Extending Reach Beyond LEO: DRM 5 Asteroid Redirect – Robotic Spacecraft	Enhancing	2015	2018	2015	1 year
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	1 year
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	3 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surfac	Enhancing	2027	2027	2021	3 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	3 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	3 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	3 years

1.4 Ancillary Propulsion Systems
1.4.6 Pyro and Separation Systems

1.4.6.1 Low-Cost Separation Systems for Nano-Launch Vehicle Systems

TECHNOLOGY

Technology Description: This technology provide separation using commercial-off-the-shelf (COTS) or additive manufacturing components that enhance affordability and meet reduced performance and reliability requirements.

Technology Challenge: Launch on demand of small satellites to optimize orbits.

Technology State of the Art: There are a variety of potential options, all based on alternate applications, or advanced production techniques.

Parameter, Value:
Cost not adequately quantified at this time.

TRL 3

Technology Performance Goal: Decrease launch costs through manufacturing of lower cost stage separation system components.

Parameter, Value:
Cost to launch 100 lbm payload to low-Earth orbit (LEO): $1.5 M

TRL 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Low-cost separation systems for small nano-launcher class vehicle.

Capability Description: Ability to conduct a cost-effective dedicated launch of a small satellite to a specified orbit within a reasonable time frame (hours to days) of the desired need date.

Capability State of the Art: Current small satellite launch is dependent on rideshare with larger satellites on larger launch vehicles, and subject to the time and orbit constraints of the larger payload, often requiring waits of month to years for launch and costing approximately three times as much per pound to orbit as for a large satellite.

Parameter, Value:
Cost to launch 100 lbm payload to LEO: $10 M

Capability Performance Goal: Decrease launch costs through manufacturing of lower cost stage separation system components.

Parameter, Value:
Cost to launch 100 lbm payload to LEO: $1.5 M

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Suborbital: Science, Research & Technology (Suborbital Program)	Enhancing	--	On-going	--	3 years
Suborbital: Earth Venture Suborbital	Enhancing	--	On-going	--	3 years
Explorer Class: Explorer Missions	Enhancing	--	2023	2020	3 years

1.4 Ancillary Propulsion Systems
1.4.7 Fundamental Ancillary Propulsion Technologies

1.4.7.1 Advanced Materials for Propulsion Applications

TECHNOLOGY

Technology Description: Advancements in materials can be used in a variety of propulsion system technology applications.

Technology Challenge: Material compatibility to extreme rocket environments.

Technology State of the Art: Dependent on specific applications.

Parameter, Value:	TRL
Dependent on specific applications.	Dependent on specific applications.

Technology Performance Goal: Improvements in material compatibility, thermal properties, and strength.

Parameter, Value:	TRL
Dependent on specific applications.	Dependent on specific applications.

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: These are advanced materials that can be used for a variety of propulsion applications.

Capability Description: Critical to advanced for all ancillary systems. Material improvements advance the state of the art by improving material properties, material compatibility, and reducing weigh and cost.

Capability State of the Art: Many materials are currently providing minimum functionality; however, these could be improved.

Parameter, Value:
Derived for specific applications.

Capability Performance Goal: Derived for specific applications.

Parameter, Value:
Derived for specific applications.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	4 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	4 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	4 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	6 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	6 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	6 years

1.4 Ancillary Propulsion Systems
1.4.7 Fundamental Ancillary Propulsion Technologies

1.4.7.2 Comprehensive Pyrotechnic Component Modeling Tool

TECHNOLOGY

Technology Description: An integrated, physics-based comprehensive analytical tool capable of directly supporting design and analysis activities for pyrotechnic.

Technology Challenge: Adequate characterization of component performance.

Technology State of the Art: General-purpose multi-physics numerical simulation programs such as LS-DYNA are used, but have limited applicability.

Parameter, Value:
LS-DYNA provides value when supplemented with necessary empirical test data to improve predictions for specific hardware.

TRL 3

Technology Performance Goal: Adequately characterize pyro component performance without extensive testing.

Parameter, Value:
There is potential to optimize pyro component performance and operational margin with much less testing.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Physics based multi-application design and analysis capability for pyrotechnic devices.

Capability Description: This is a comprehensive pyrotechnic component computer modeling tool, anchored with testing, to reduce the development cost and schedule impact of new pyrotechnic component designs.

Capability State of the Art: Disintegrated analysis and design capabilities. Current capability does not allow direct use in design and analysis resulting in comprehensive testing in most cases (i.e., current Commercial Crew Frangible Joint testing).

Parameter, Value:
Developmental timelines as well as overall project cost reductions could occur.

Capability Performance Goal: Provide a comprehensive pyrotechnic component computer modeling tool, anchored with testing, to reduce the development cost and schedule impact of new pyrotechnic component designs.

Parameter, Value:
Lower cost and less empirical approach to pyrotechnic systems design and development.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	4 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	4 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	4 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	6 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	6 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	6 years

1.4 Ancillary Propulsion Systems
1.4.7 Fundamental Ancillary Propulsion Technologies

1.4.7.3 Physics-Based Modeling for Ancillary Propulsion Systems

TECHNOLOGY

Technology Description: Support development of auxiliary control, main propulsion, launch abort, and thrust vector control (TVC) systems.

Technology Challenge: Coupling the individual physics-based models and then validating the coupled capabilities.

Technology State of the Art: High-fidelity tools exist with some limited coupling. Coupled physics capabilities are largely unvalidated.

Parameter, Value: Partially validated, uncoupled physics models.

TRL: 4

Technology Performance Goal: Validate high fidelity, physics-based, tightly-coupled computational models to enable robust ancillary propulsion system designs that lower the cost of access to space.

Parameter, Value: Validated, tightly-coupled fluid-thermal-structural design tool.

TRL: 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: High-fidelity design tools to support design of robust solid and liquid ancillary propulsion systems can significantly lower design, development, test, and evaluation (DDT&E) and production costs.

Capability Description: An ancillary propulsion system design process that results in robust hardware can lower DDT&E and production costs.

Capability State of the Art: Currently used as the stand-alone capabilities with limited coupling capability.

Parameter, Value: Developmental timelines as well as overall project cost reductions could occur.

Capability Performance Goal: Reduce time and cost of design cycles.

Parameter, Value: Lower system costs by at least 15-25% and decrease time for hardware delivery by at least 20%.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	4 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	4 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	4 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	6 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	6 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	6 years

1.5 Unconventional and Other Propulsion Systems
1.5.2 Air Launch and Drop Systems

1.5.2.1 Towed Glider Air Launch System

TECHNOLOGY

Technology Description: This is an air launch system that uses a remotely/autonomously piloted glider to carry a small launch vehicle to altitude and near-vertical orientation for launch without use of a traditional launch range. The glider and launch vehicle are towed to altitude by a minimally modified existing aircraft and released from tow prior to launch.

Technology Challenge: Launch on demand of small satellites to optimize orbits.

Technology State of the Art: Concepts have been developed for a towed glider as part of an orbital launch system. Towed glider technology for other applications is mature. Application as a payload delivery system must be developed.

Parameter, Value: No demonstrated performance capability exists.

TRL: 4

Technology Performance Goal: Produce a towed glider air launch system capable of carrying various small launch vehicle sizes and shapes to optimized air launch coordinates and conditions within 24 hours of satellite and launch vehicle delivery.

Parameter, Value: Cost to launch 100 lbm payload to low-Earth orbit (LEO): $1.5 M

TRL: 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Cost-effective launch-on-demand for small satellite payloads.

Capability Description: Ability to conduct a cost-effective dedicated launch of a small satellite to a specified orbit within a reasonable time frame (hours to days) of the desired need date.

Capability State of the Art: Current small satellite launch is dependent on rideshare with larger satellites on larger launch vehicles, and subject to the time and orbit constraints of the larger payload, often requiring waits of month to years for launch and costing approximately three times as much per pound to orbit as for a large satellite.

Parameter, Value: Cost to launch 100 lbm payload to LEO: $10 M

Capability Performance Goal: Decrease launch costs through more efficient integration, launch, and range clearance.

Parameter, Value: Cost to launch 100 lbm payload to LEO: $1.5 M

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Suborbital: Science, Research & Technology (Suborbital Program)	Enhancing	--	On-going	--	3 years
Suborbital: Earth Venture Suborbital	Enhancing	--	On-going	--	3 years
Explorer Class: Explorer Missions	Enhancing	--	2023	2020	3 years

1.6 Balloon Launch Systems
1.6.1 Super-Pressure Balloon

1.6.1.1 Extended Duration Super-Pressure Balloon (SPB)

TECHNOLOGY

Technology Description: This is a super pressure balloon (SPB) with a volume of 18.8 million cubic feet.

Technology Challenge: SPB technical challenges include manufacturing, materials, and analysis.

Technology State of the Art: One of three required test flights of the 18.8 million cubic foot balloon has been completed.

Parameter, Value:

Float duration: 2 hours;

Payload capacity: ~2,268 kg;

Altitude: 33.5 km

TRL 7

Technology Performance Goal: The goal is to provide the science community a stable stratospheric balloon platform at mid-latitudes and polar locations to conduct science investigations.

Parameter, Value:

Float duration: 60 to 100 days;

Payload capacity: ~2,268 kg;

Altitude: 33.5 km

TRL 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Flight Opportunities during the FY 2015 Antarctica and New Zealand Campaigns

CAPABILITY

Needed Capability: Extended-duration pressurized balloon.

Capability Description: The SPB can be used for extended mid-latitude float durations for up to 100 days in the stratosphere for large science payloads as well as constant altitude polar flights. The 18.8 million cubic foot balloon would carry 2,268 kg to 33.5 km.

Capability State of the Art: Currently, only Zero Pressure Balloon (ZPB) polar flights in constant sunlight are capable of flight durations of several weeks to months with altitude variations of 4.5 km. Currently no mid-latitude ZPB capability exists beyond 1-2 day turnaround flights.

Parameter, Value:

Polar float duration: 1 to 55 days;

Mid-latitude float durations: 1 to 2 days;

Payload capacity: up to 3,628 kg;

Altitude: 33 to 40 km

Capability Performance Goal: Mid-latitude flight durations are limited due to the altitude variations exhibited by ZPB's. The SPB will provide extended float durations for large scientific payloads for up to 100 days. In addition, the SPB will allow for polar flights at a stable float altitude.

Parameter, Value:

Float durations: 60 to 100 days;

Payload Capacity: ~2,268 kg;

Altitude: 33.5 km

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Suborbital: Science, Research & Technology (Suborbital Program)	Enabling	--	On-going	--	1 year
Explorer Class: Explorer Missions	Enabling	--	2023	2020	1 year

1.6 Balloon Launch Systems
1.6.1 Super-Pressure Balloon

1.6.1.2 Higher-Altitude Extended Duration Super-Pressure Balloon (SPB)

TECHNOLOGY

Technology Description: This is a super pressure balloon (SPB) with a volume of 26 million cubic feet.

Technology Challenge: SPB technical challenges include manufacturing, materials, and analysis.

Technology State of the Art: A 26 million cubic foot balloon has not been built or test flown yet.

Parameter, Value:	TRL
Float duration: 0 days; Payload capacity: ~1,814 kg; Altitude: 35.7 km	2

Technology Performance Goal: Provide the science community a stable stratospheric balloon platform at mid-latitudes and polar locations to conduct science investigations.

Parameter, Value:	TRL
Float duration: 60 to 100 days; Payload capacity: 1,814 kg; Altitude: 35.7 km	9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Outcome of lower altitude SPB, Technology Readiness Level (TRL) advancement based on on-going Finite Element Modeling, and test and launch opportunities in FY 2016

CAPABILITY

Needed Capability: Higher-altitude extended duration pressurized balloon.

Capability Description: The higher-altitude SPB can be used for extended mid-latitude float durations for up to 100 days in the stratosphere for large science payloads as well as constant altitude polar flights. The 26 million cubic foot would carry 1,814 kg to 35.7 km.

Capability State of the Art: Currently, only Zero Pressure Balloon (ZPB) polar flights in constant sunlight are capable of flight durations of several weeks to months with altitude variations of 4.5 km. Currently no mid-latitude ZPB capability exists beyond 1-2 day turnaround flights.

Parameter, Value:

Polar float durations: 1 to 55 days;

Mid-latitude float durations: 1 to 2 days;

Payload capacity: up to 3,628 kg;

Altitude: 33 to 40 km

Capability Performance Goal: Provide longer float durations in mid-latitudes with minimal altitude loss during diurnal cycles.

Parameter, Value:

Float duration: 60 to 100 days;

Payload capacity: 1,814 kg;

Altitude: 35.7 km

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Suborbital: Science, Research & Technology (Suborbital Program)	Enabling	--	On-going	--	1 year
Explorer Class: Explorer Missions	Enabling	--	2023	2020	2 years

1.6 Balloon Launch Systems
1.6.2 Materials

1.6.2.1 Lightweight Gondola and Flight Train Systems

TECHNOLOGY

Technology Description: Reduced mass of flight train components, such as gondolas and cable ladders.

Technology Challenge: Manufacturing, materials, and analysis.

Technology State of the Art: Aluminum and steel structures and assemblies.

Parameter, Value: Various strength-to-mass ratios

TRL: 9

Technology Performance Goal: Produce lighter weight materials (composites, synthetic cables, etc.) for use in flight train systems to increase mass allocation to science payload.

Parameter, Value: Higher strength-to-mass ratios

TRL: 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Application and testing of known materials advancement into current designs, redesign, and testing to allow for enhanced materials use

CAPABILITY

Needed Capability: Lightweight balloon mechanical systems.

Capability Description: This technology maximizes the mass available for science.

Capability State of the Art: Aluminum and steel structures and assemblies.

Parameter, Value: Various strength-to-mass ratios

Capability Performance Goal: Higher strength to mass ratios.

Parameter, Value: Higher strength-to-mass ratios

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Suborbital: Science, Research & Technology (Suborbital Program)	Enhancing	--	On-going	--	2 years

1.6 Balloon Launch Systems
1.6.3 Pointing Systems

1.6.3.1 Arc Second Balloon Pointing Systems

TECHNOLOGY

Technology Description: The Wallops Arc Second Pointing (WASP) system is used for fine pointing of large balloon science instruments.

Technology Challenge: The design, manufacturing, analysis of electronic and mechanical systems, and software development represent major technical challenges.

Technology State of the Art: The fine pointing system (WASP) has had four test flights and is close to full qualification.

Parameter, Value: Pointing accuracy: ~1 arc second

TRL: 7

Technology Performance Goal: Enable precision pointing of large balloon science instruments.

Parameter, Value: Pointing accuracy: < 1 arc second

TRL: 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Adequate demonstrated performance

CAPABILITY

Needed Capability: This is a balloon pointing system.

Capability Description: Provides the ability to point science instruments with high accuracy during balloon flight.

Capability State of the Art: With arcsecond and sub-arcsecond pointing, exoplanet and planetary investigations can be conducted on from a balloon platform.

Parameter, Value: Pointing accuracy: ~1-5 arc second

Capability Performance Goal: Enable precision pointing of large balloon science instruments to enable exoplanet and planetary studies from balloon platforms.

Parameter, Value: Pointing accuracy: ~1 arc second

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Suborbital: Science, Research & Technology (Suborbital Program)	Enabling	--	On-going	--	1 year
Explorer Class: Explorer Missions	Enabling	--	2023	2020	1 year

1.6 Balloon Launch Systems
1.6.4 Telemetry Systems

1.6.4.1 Balloon Telemetry Systems

TECHNOLOGY

Technology Description: Telemetry systems improve data download speeds and overall quantity.

Technology Challenge: Power requirements, mass allocation, and cost.

Technology State of the Art: Balloon telemetry systems currently use IRIDIUM and Tracking and Data Relay Satellite System (TDRSS).

Parameter, Value:

Data rate: 200,000 bps (two commercial satellites);

Data rate: 100,000 bps (commercial system);

Data rate: 150,000 bps (TDRSS)

TRL

9

Technology Performance Goal: Provide higher over-the-horizon data rates from balloon flights.

Parameter, Value:

Data rate: > 400,000 bps

TRL

9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Transceiver technology advancements

CAPABILITY

Needed Capability: Improved balloon communications systems.

Capability Description: Affordable faster data download over 200,000 bps using satellite relay.

Capability State of the Art: Current systems use satellite relay links and have data rates up to 150,000 bps.

Parameter, Value:

Commercial system data rate: 100 kbps (up to 2 systems for 200 kbps);

TDRSS data rate: 150,000 bps (TDRSS transceiver and high gain antenna)

Capability Performance Goal: Enable science users to obtain higher data rates to download more or all of their data.

Parameter, Value:

Data rate: > 400,000 bps

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Suborbital: Science, Research & Technology (Suborbital Program)	Enhancing	--	On-going	--	1 year
Explorer Class: Explorer Missions	Enhancing	--	2023	2020	1 year

1.6 Balloon Launch Systems
1.6.5 Balloon Trajectory Control

1.6.5.1 Balloon Trajectory Control System

TECHNOLOGY

Technology Description: Cross-track influence of ~1 m/s over duration that allows a mid-latitude balloon flight to avoid populated areas, steer around bad storms, and guide payloads to specific locations where termination and recovery is highly probable.

Technology Challenge: The environment in which stratospheric balloons fly makes it difficult to impart a force to the very large balloons.

Technology State of the Art: No capability exists today. Several different methods proposed, but none demonstrated in flight. Small scale concepts have been tested with positive results.

Parameter, Value:
Cross-track influence: 0 m/s

TRL 4

Technology Performance Goal: Alter the trajectory path of a stratospheric balloon.

Parameter, Value:
Cross-track influence: ≥ 1 m/s

TRL 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Availability of funding and adequate demonstrated performance

CAPABILITY

Needed Capability: Balloon trajectory control.

Capability Description: Longer-duration flights could be enhanced through modification of the free floating balloons trajectory. Moderate trajectory control would allow both avoiding overflight of populated areas as well as guiding systems to safe termination areas at the end of the flight.

Capability State of the Art: No capability exists today.

Parameter, Value:
Cross-track influence: 0 m/s

Capability Performance Goal: Alter the trajectory path of a stratospheric balloon.

Parameter, Value:
Cross-track influence: ≥ 1 m/s

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Suborbital: Science, Research & Technology (Suborbital Program)	Enhancing	--	On-going	--	2 years
Explorer Class: Explorer Missions	Enhancing	--	2023	2020	2 years

1.6 Balloon Launch Systems
1.6.6 Power Systems

1.6.6.1 Balloon Power Systems

TECHNOLOGY

Technology Description: Science users require higher power systems to power science payloads as well as the potential for power systems that can handle long nighttime exposures.

Technology Challenge: Major challenges for this technology include design, manufacturing, and analysis of electronic and mechanical systems.

Technology State of the Art: Terrestrial solar cells and nickel-metal hydride (NiMH) batteries.

Parameter, Value:
Power generation: up to 1,000 watts;
Power storage: up to 12,000 watt hours

TRL: 9

Technology Performance Goal: Higher power systems and higher efficiency power systems.

Parameter, Value:
Power generation: ~2,000 watts;
Power storage: ~24,000 watt hours

TRL: 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Battery technology advancements

CAPABILITY

Needed Capability: Higher power generation and storage systems for payload support

Capability Description: Advanced solar panel rechargeable systems and modular power system for science.

Capability State of the Art: Solar panel power generation using terrestrial solar cells and NiMH batteries for power storage.

Parameter, Value:
Power generation: up to 1,000 watts;
Power storage: up to 12,000 watt hours

Capability Performance Goal: Higher power systems and higher efficiency power systems.

Parameter, Value:
Power generation: ~2,000 watts;
Power storage: ~24,000 watt hours

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Suborbital: Push	Enhancing	--	--	--	2 years

1.6 Balloon Launch Systems
1.6.7 Mechanical Systems: Launch Systems

1.6.7.1 Low Density Supersonic Decelerator (LDSD) Static Launch Tower

TECHNOLOGY

Technology Description: A launch system that can be operated by people remotely is required for large hazardous payload (like rocket motor) launches. Safety of personnel, equipment, and infrastructure are paramount.

Technology Challenge: The launch tower must be tall enough to handle potential pendulum motion of payload upon release. Boom holding payload must not come in contact with payload after release. Flight train must not get tangled in launch tower.

Technology State of the Art: System has been developed.

Parameter, Value:	TRL
Remotely launched balloon payload, payload mass: 3,630 kg	9

Technology Performance Goal: To be able to launch up to 3,630 kg, remotely.

Parameter, Value:	TRL
Remotely launched balloon payload, payload mass: 3,630 kg	9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Successful launch demonstration of LDSD, June/July 2014. Additional Flights are planned for FY 2015

CAPABILITY

Needed Capability: Mechanical systems: balloon launch systems.

Capability Description: This technology provides an ability to launch large balloons with minimal ground interaction by personnel for safety reasons.

Capability State of the Art: Currently, a mobile launch vehicle is used for the launch of large scientific balloons. This requires numerous personnel to be located within feet of the balloon payload.

Parameter, Value:

Remotely launched balloon payload mass: 3,630 kg;

Safety zone: 152 meters

Capability Performance Goal: To be able to launch up to 3,630 kg, remotely.

Parameter, Value:

Payload mass: 3,630 kg;

Safety zone: 152 meters

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Suborbital: Science, Research & Technology (suborbital program)	Enabling	--	On-going	--	1 year

1.6 Balloon Launch Systems
1.6.8 Mechanical Systems: Parachute

1.6.8.1 Ultraviolet Protection for Parachutes

TECHNOLOGY

Technology Description: Provide ultraviolet (UV) protection for parachutes designed for ultra-long-duration flights.

Technology Challenge: Design, manufacturing and analysis of materials.

Technology State of the Art: Flat, circular, nylon parachutes.

Parameter, Value:
Duration: 30-50 days

TRL: 9

Technology Performance Goal: To maintain parachute strength over a 100 day flight.

Parameter, Value:
Duration: 100+ days

TRL: 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Mechanical systems: parachutes for balloon flights.

Capability Description: The addition of UV protection to parachutes for extra protection during ultra-long-duration flights.

Capability State of the Art: No additional protection currently added to parachutes.

Parameter, Value:
Duration: 30-50 days

Capability Performance Goal: To maintain parachute strength over a 100 day flight.

Parameter, Value:
Duration: 100+ days

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Suborbital: Push	Enhancing	--	--	--	2 years

1.6 Balloon Launch Systems
1.6.9 Mechanical Systems: Floatation

1.6.9.1 Mechanical Systems: Floatation for Balloon Payloads

TECHNOLOGY

Technology Description: Payload floatation to accomplish recovery of longer-duration flights in mid-latitudes.

Technology Challenge: Design, manufacturing, and analysis of electronic and mechanical systems.

Technology State of the Art: No capability exists today. Large scale concepts have been demonstrated and may be scalable for this use.

Parameter, Value: Current payloads have no provision for floatation.

TRL: 2

Technology Performance Goal: Enable floatation of payloads up to 3,630 kg for durations of up to several weeks in a saltwater environment.

Parameter, Value:
Float duration: > 10 days;
Payload capacity: 3,630 kg

TRL: 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Identification of low mass solution adaptable to balloon gondolas

CAPABILITY

Needed Capability: Mechanical systems: floatation for balloon payloads.

Capability Description: Floatation would be required for payloads impacting in the ocean so recovery could be performed. Payload weights could range from hundreds of pounds up to 3,630 kg. Floatation for several days to weeks in a saltwater environment.

Capability State of the Art: No floatation capability is currently used by NASA for payloads.

Parameter, Value:
Float duration: 0 weeks;
Payload capacity: 0 kg

Capability Performance Goal: Enable floatation of payloads up to 3,630 kg for durations of up to several weeks in a saltwater environment.

Parameter, Value:
Float duration: 3 weeks;
Payload capacity: 3,630 kg

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Suborbital: Push	Enhancing	--	--	--	2 years